

**THE EFFECTS OF LONGWALL COAL MINING ON THE HYDROGEOLOGY OF  
SOUTHWESTERN PENNSYLVANIA**

by

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# **THE EFFECTS OF LONGWALL COAL MINING ON THE HYDROGEOLOGY OF SOUTHWESTERN PENNSYLVANIA**

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University of Pittsburgh, 2010

The purpose of this study is to investigate the susceptibility characteristics of domestic and agricultural water supplies that may be vulnerable to diminution or total loss in supply when active longwall mining is in the vicinity of the potable aquifer systems of Southwestern, Pennsylvania. Susceptibility characteristics include hydrogeologic setting, proximal location to mining, and climatic conditions at the time of impact. The investigation serves the purpose of enhancing our understanding and will aid in predicting potential impacts during future undermining of water sources such as wells and springs. The investigation will demonstrate an understanding of the pre and post-mining behavior of hydrologic systems by considering the relationship between the geologic and mining characteristics. Geologic characteristics include overburden composition and geomorphology of the surface. Mining characteristics include mining method, overburden depth, extraction thickness, etc.

The study focuses on water supplies in Greene and Washington Counties with reported losses or reductions in supply that were attributed to the seven active longwall mines in operation between 2003 and 2008. The undermined water supplies represent a variety of hydrogeologic settings and mining conditions prevalent in the Southwestern Pennsylvania longwall coalfield. The knowledge gained from this analysis can be used to more adequately plan for potential disruptions in water supplies subjected to longwall coal mining and the local conditions that may better predict the vulnerability of water supplies to interruption or loss of the supply.

## TABLE OF CONTENTS

<b>1.0</b>	<b>INTRODUCTION.....</b>	<b>1</b>
<b>1.1</b>	<b>PURPOSE.....</b>	<b>4</b>
<b>2.0</b>	<b>METHOD OF STUDY .....</b>	<b>5</b>
<b>3.0</b>	<b>PRE-MINING HYDROGEOLOGY OF STUDY AREAS .....</b>	<b>9</b>
<b>4.0</b>	<b>LONGWALL MINING IMPACTS ON HYDROLOGY.....</b>	<b>14</b>
<b>4.1</b>	<b>SUBSIDENCE THEORY.....</b>	<b>15</b>
<b>4.2</b>	<b>GREENE AND WASHINGTON COUNTY WATER SUPPLIES.....</b>	<b>23</b>
<b>5.0</b>	<b>CHARACTERISTICS OF SUSCEPTIBILITY.....</b>	<b>27</b>
<b>5.1</b>	<b>HYDROGEOLOGIC SETTING.....</b>	<b>28</b>
<b>5.1.1</b>	<b>TOPOGRAPHY .....</b>	<b>28</b>
<b>5.1.2</b>	<b>OVERBURDEN .....</b>	<b>29</b>
<b>5.1.3</b>	<b>HYDROGEOLOGIC LOCATION SCENARIO .....</b>	<b>31</b>
<b>5.2</b>	<b>PROXIMAL LOCATION TO MINING .....</b>	<b>33</b>
<b>5.2.1</b>	<b>HYDROLOGIC ANGLE OF INFLUENCE.....</b>	<b>33</b>
<b>5.2.2</b>	<b>PANEL LOCATION .....</b>	<b>35</b>
<b>5.3</b>	<b>CLIMATIC CONDITIONS AT TIME OF IMPACT.....</b>	<b>38</b>
<b>5.3.1</b>	<b>LONG-TERM AVERAGE PRECIPITATION RATES.....</b>	<b>38</b>
<b>5.3.2</b>	<b>SEASONAL INFILTRATION RATES.....</b>	<b>40</b>
<b>5.4</b>	<b>MINE INFLOW .....</b>	<b>42</b>

5.5	RESOLUTIONS TO IMPACTS .....	44
6.0	UNDERMINING CHARACTERISTICS BY MINE .....	45
7.0	SUMMARY .....	49
8.0	CONCLUSION.....	51
	APPENDIX A .....	52
	APPENDIX B .....	54
	BAILEY MINE WATER SUPPLIES.....	55
	BAILEY MINE OVERBURDEN .....	56
	BLACKSVILLE NO. 2 MINE WATER SUPPLIES .....	57
	BLACKSVILLE NO. 2 MINE OVERBURDEN.....	58
	CUMBERLAND MINE WATER SUPPLIES.....	59
	CUMBERLAND MINE OVERBURDEN.....	60
	EMERALD MINE WATER SUPPLIES.....	61
	EMERALD MINE OVERBURDEN .....	62
	ENLOW FORK MINE WATER SUPPLIES .....	63
	ENLOW FORK MINE OVERBURDEN.....	64
	HIGH QUALITY MINE WATER SUPPLIES .....	65
	HIGH QUALITY MINE OVERBURDEN .....	66
	MINE 84 WATER SUPPLIES .....	67
	MINE 84 OVERBURDEN.....	68
	BIBLIOGRAPHY .....	69

## LIST OF TABLES

Table 4.1: Average panel widths, depths, critical panel widths, and classifications for each longwall mine.....	16
Table 4.2: Total number of undermined and impacted water supplies per longwall mine.....	25
Table 4.3: Percentage of impacted water supplies by mine.....	26
Table 5.1: Number of water supplies unaffected and impacted based on their topographic location.....	29
Table 5.2: Number of water supplies unaffected and impacted based on their overburden classification .....	30
Table 5.3: Number of water supplies unaffected and impacted based on their location scenario	31
Table 5.4: Number of impacted water supplies (n=106) tabulated by month of occurrence.....	39
Table 5.5: Number of water supplies impacted based on month of undermining; left side- high groundwater recharge months and right side- months with high rates of evapotranspiration.....	41
Table 5.6: The mine inflow rates (rates of pumping required) for each longwall mine .....	42

## LIST OF FIGURES

Figure 1.1: Plan view of generic longwall mine .....	2
Figure 3.1: Natural valley stress relief fractures (Wyrick and Borchers 1981). .....	12
Figure 4.1: A schematic showing the three subsidence basin types (D’Appolonia 2009). .....	18
Figure 4.2: Depiction of the four subsidence zones (Peng 2008) .....	19
Figure 4.3: Zones of compression and tensile strata fracturing (Booth 1986).....	20
Figure 4.4: Hydrologic response zones (Kendorski and Consultants 1993).....	21
Figure 4.5: Average longwall panel’s approximate hydrologic response zones; adapted from (Kendorski and Consultants 1993; Peng 2008). .....	22
Figure 4.6: Greene County and the location of the four active mines of the study .....	23
Figure 4.7: Washington County and the location of the three active mines of the study .....	24
Figure 4.8: Number of undermined (n=1,214) and impacted (n=106) water supplies .....	25
Figure 5.1: Raster images for surface elevations (left) and slopes (right) used to classify water supplies .....	28
Figure 5.2: Percentage of impacted water supplies based on location scenario. ....	32
Figure 5.3: Distribution of angles of influence for impacted water supplies.....	34
Figure 5.4: Panel classification locations and stress location cross-section .....	35
Figure 5.5: Percentage of impacted water supplies at each longwall panel location.....	37
Figure 5.6: Precipitation totals compared to the long-term precipitation averages for Waynesburg .....	39
Figure 6.1: Mine impact rates compared to percentage of hilltop supplies undermined by mine	46
Figure 6.2: Mine impact rates compared to average overburden of the mine .....	47
Figure 6.3: Mine impact rates compared to percentage of water supplies undermined by a longwall panel.....	48

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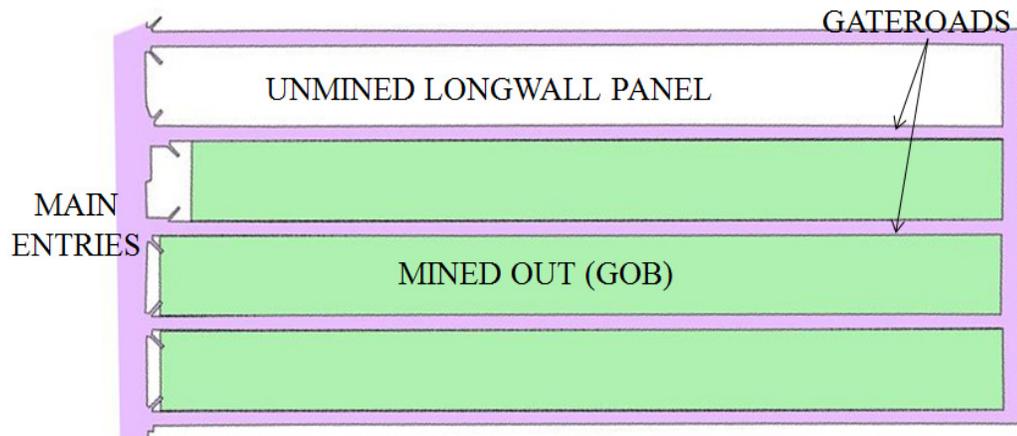
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## 1.0 INTRODUCTION

Underground coal mining plays an integral role in Southwestern Pennsylvania's economy. The production of energy resources is vital to the everyday operations of the region and to the country. It is estimated that Southwestern Pennsylvania's underground bituminous coalfields have produced approximately 52 million short tons of coal annually in recent years (Administration 2010). The mining methods used to extract coal, in this study, include longwall mining and room-and-pillar mining.

Longwall mines consist of a series of coal panels which can be over 1,000-feet (ft) in width and up to three miles in length. Prior to extraction, the dimensions of the panels are developed by gateroads. Gateroads are produced by the room-and-pillar method and are a series of entries and crosscuts which leave large pillars of coal for roof support. The gateroads are necessary for the movement of miners, machinery, and coal; as well as for the safe ventilation of the mining face. Figure 1.1 presents a plan view of a generalized longwall mine configuration. Longwall extraction is performed using a series of mechanized hydraulic roof supports, known as shields. A double drummed shearer is used to strip the face of the coal. As the coal face is stripped, crushed, and removed via a conveyor system, the shields move forward causing the roof to cave behind the shields. After the immediate roof rock caves into the mine void, the subsequent layers of the overburden strata become unstable and cave, fracture, or deform. The caved area of a mined longwall panel is known as the gob. The propagation of strata instability

to the ground surface is called subsidence. The characteristics of subsidence and the creation of a subsidence basin will be discussed further in Section 4.0.



**Figure 1.1:** Plan view of generic longwall mine

Surface features such as structures, roadways, water supplies, streams, and wetlands that are located above or adjacent to underground coal mines can be affected by the subsidence caused by mining. In 1966, legislation was passed, known as the Bituminous Mine Subsidence Land Conservation ACT (BMSLCA) with the intention of providing protection to surface features located above active coal mines. In 1994, an amendment to BMSLCA was passed, known as ACT 54. This amendment further addresses surface property owner rights, coal mine operator responsibilities, and Pennsylvania Department of Environmental Protection (PA DEP) regulatory responsibilities. Surface features that are impacted by mining are the mine operator's responsibility to replace, repair, or provide compensation to a surface property owner for the damages. Mine operators are also required to submit extensive permit applications which document the pre-mining conditions of surface features. The legislation holds the PA DEP responsible for ensuring that impacts to surface features are minimized, mining companies are

operating under their permits, any mining induced impacts to surface features are repaired by the mine operator within a reasonable time period, and that an impact resolution has been achieved between land owners and mine operators.

ACT 54 also mandates that the investigations and impact resolution efficiency of the PA DEP and mine operators be reported and made public every five years. The University of Pittsburgh was contracted to conduct the five year assessment for the years 2003 to 2008 (Iannacchione, Tonsor et al. 2010). The data reported in the PA DEP and University of Pittsburgh contract assessment report and the data presented in this study are nearly the same. The minor differences will be addressed in Section 2.0.

## **1.1 PURPOSE**

Between 2003 and 2008, there were seven longwall mines in operation in Greene and Washington Counties. The seven longwall mines mined a total of 78 longwall panels of varying length and width. On average, these panels were 218 acres, and a total of 17,675 acres were undermined using the longwall panel extraction technique over the five year period. The total acreage, including the room-and-pillar sections for all seven longwall mines, was approximately 24,535 acres. A map showing the location of the active longwall mines and the extent of mining throughout the five year period is contained in Appendix A.1.

Because this technique is widely utilized in Southwestern Pennsylvania the purpose of this study is to explore the susceptibility characteristics of shallow aquifer water supplies that may be vulnerable to a water loss or reduction in supply when active longwall mining is in the vicinity. By better understanding the hydrogeologic response of the overburden strata to longwall mining, occurrences of water supply losses can be predicted more accurately. Proper prediction and assessment of these susceptibility characteristics may be beneficial for the planning of mining operations or for regulatory agencies when determining the cause of a reported water supply impact.

## 2.0 METHOD OF STUDY

The 3<sup>rd</sup> assessment report on the impacts of underground bituminous coal mining on the Commonwealth of Pennsylvania was completed by the University of Pittsburgh for the time period from August 2003 to August 2008 (Iannacchione, Tonsor et al. 2010). A portion of the data procured in the University's assessment report is utilized in this study, and the processes and methodology of data procurement is outlined below:

- An intensive search of the PA DEP's Bituminous Underground Mine Information System (BUMIS) was completed. The BUMIS database is a tool used by the PA DEP to track the status of the land features undermined by bituminous coal mining in Western Pennsylvania by individual mines. Information regarding the property number, feature type and use, and if an effect of mining was reported were compiled in tabular format for all water supplies undermined in the five year assessment period.
- The PA DEP provided the University with 6-month mining maps for each active mine in the study period. These maps detail the mining that occurred six months prior to submission, the intended location of mining six months in advance of submission, and the locations of the surface features undermined by each mine. The PA DEP defines a surface feature as being undermined if it within 200-ft of active mining. These maps were spatially located, or georeferenced, into the University's Geographic Information System (GIS) database, using prominent surface features or landmarks

located on the maps. The GIS database was created using ArcGIS software. The extent of longwall mining, room-and-pillar mining, and locations of the water supplies were then digitized into the GIS database. The dates of mining were input as characteristic attributes, and each water supply that was digitized was given a unique identifier.

- The purpose of the GIS database is to establish a link between the spatial locations of surface features on the maps to the tabular, or characteristic, data collected from the BUMIS database search. The tabular data was joined to the spatial location point on the map using the unique identifier, allowing the tabular information to be characteristic attributes of the spatial location in the GIS database.
- Additional characteristics were attributed to each water supply with the creation of overburden maps and surface elevation contours. The maps were created from GIS spatial layers that were gathered from the Pennsylvania Spatial Data Access (PASDA) and U.S. Geological Survey (USGS) online spatial databases. The characteristic measurements (i.e. overburden depth and surface elevation) were calculated by ArcGIS and automatically added to the attribute tables. The distance to mining, topographic relief characteristics (i.e. hilltop, hillside, or valley bottom), location with respect to the longwall panel (i.e. mid-panel, quarter panel, gateroad, or outside), and approximate date of undermining were manually input into the attribute tables.
- Additional information regarding the pre-mining water supply characteristics (i.e. well depth, spring production rates, etc.) were determined by exploring the Module 8 section of the permit files located at the California District Mining Office (CDMO).

Module 8 is the hydrology section of the permit application submitted by each mine operator, which contains details regarding the natural hydrology of the mine's location, a water supply inventory, background or pre-mining sampling, a description of the prediction of hydrologic consequence, the means of protecting the hydrologic balance, and a hydrologic monitoring plan.

- The complete database was used to determine the vulnerability statistics of the undermined water supplies, as well as to create maps to visually represent the mining locations and their undermined surface features.

The limitations of this study include:

- Mining during a five year period was only considered; therefore any locations of mining conducted before 2003 and after 2008 were not considered. As a result, water supplies classified as being located outside of active mining during the assessment may actually have been undermined.
- Water supply characteristics (i.e. depth to water, production rates) were not able to be determined for the majority of supplies. These quantitative water supply measurements, previous to and during mining, would have helped to determine water level changes caused by mining.
- Post-mining aquifer conditions were not able to be determined for the majority of water supplies. The post-mining aquifer conditions would have been useful to determine if long-term aquifer recovery occurred or if there were permanent water level changes due to mining.

A number of water supplies within the contract report (Iannacchione, Tonsor et al. 2010) were not included in this study:

- The Shoemaker Mine was not included in this study because it is located primarily in West Virginia and did not mine a considerable distance into Pennsylvania.
- Only water supplies with diminution or total loss of supply were considered in this study.
- Ponds were not considered in this study.
- The regulatory classifications of Liable and No Liability were not used to classify the water supplies in this study. Only water supplies that were impacted by mining, as determined by PA DEP descriptions, and have a resolution on record confirming the PA DEP description were included as impacted supplies. Water supplies not meeting this criteria and located outside of 200-ft of mining were not included, as well.

If compared, the contract report and this study present similar trends and concepts, but inventory totals and percentages are not the same because of the reduced data analyzed in this study.

### **3.0 PRE-MINING HYDROGEOLOGY OF STUDY AREAS**

The natural, pre-mining, hydrogeologic principles governing the strata's ability to produce adequate water supplies include geology, overburden composition, permeability, recharge/discharge locations, etc. The movement of water through the stratigraphic layers of the ground is influenced by permeability, which may be classified as primary or secondary. Primary permeability refers to the movement of water through the intergranular pore spaces of the strata layers, whereas secondary permeability refers to groundwater movement through geologic features such as fractures, bedding plane separations, joints, and cleats associated with the strata (Wyrick and Borchers 1981).

Greene and Washington County have similar geologic units, such that longwall mining occurs in the Pittsburgh coalbed. This coalbed is located in the Monongahela Group and is fairly uniform in thickness. The consistency in the coal deposition allows the longwall mining technique to be utilized effectively. The water-bearing layers of interest are therefore located between the Pittsburgh coalbed and the ground surface. The primary geologic units include the most recently deposited alluvium associated with the Pleistocene/Holocene Group, then the Dunkard Group, and finally the oldest of the units of interest, the Monongahela Group.

The water-bearing characteristics of a generalized geology of Greene and Washington counties follow:

- Pleistocene/Holocene Group: This group contains the material of the alluvium formation which has been deposited along stream valleys by the movement of water. The layer consists of a distribution of gravel, sand, silt, and clay, and this distribution will vary in different locations (Newport 1973). Depending on the soil particle distribution, the alluvial layers can be an adequate to excellent water-bearing layers because water is able to flow vertically and horizontally through the pore spaces of the soils.
- Dunkard Group: This group consists of the Greene, Washington, and Waynesburg Formations (in descending order). The Greene Formation is composed of mostly thin limestone, shale, and sandstone. The sandstone layers are the most hydrologically productive units because they contain a larger number of fractures and planes of weakness; and are therefore the most important water-bearing units in the formation. Shale and limestone units are generally poor water-bearing units because of low hydraulic conductivities and a small number of fractures. Overall, the Greene Formation's wells will yield approximately 2-gallons per minute (gpm) and tend to be located within the first 120-ft of the ground surface (Newport 1973). The Washington Formation also consists of shale, sandstone, and limestone, with the addition of several coalbeds. On average, the wells drawing water from the Washington Formation yield between two and three-gpm, and range from 30 to 300-ft deep. It is also common for the formation to discharge water as springs or seeps with average discharges around 0.50-gpm (Stoner, Williams et al. 1987). The basal layer of the Dunkard Group is the Waynesburg Formation. This formation has slightly more productive sandstone and coal

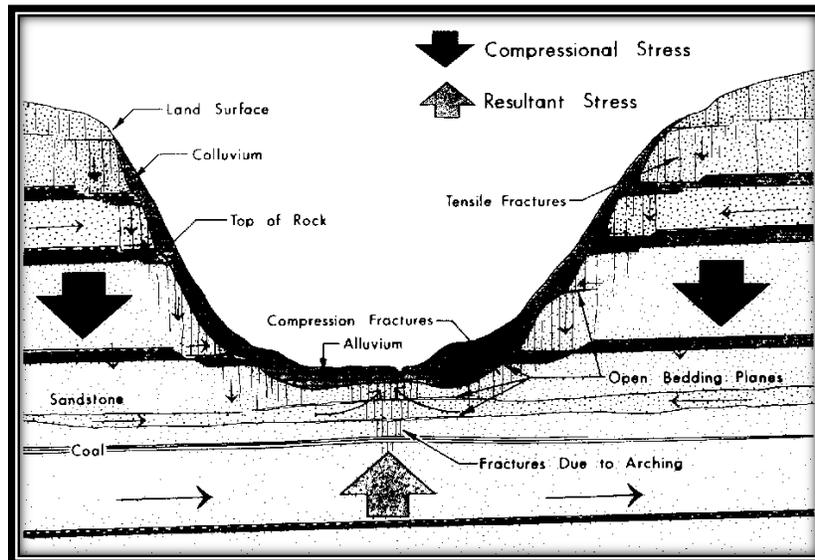
water-bearing layers, which average well yields of 3.8-gpm (Stoner, Williams et al. 1987).

- Monongahela Group: This group consists of the Uniontown and Pittsburgh Formations. The basal unit of the Pittsburgh Formation is the Pittsburgh coalbed. The formations generally consist of a combination of coal, limestone, shale, and sandstone; however, the hydrologic production capabilities vary widely across both Greene and Washington counties. In Greene County, the average well yield is 8-gpm for Uniontown Formation wells, and the Pittsburgh Formation produces sufficient quantities in the Eastern portion of Greene County as well. However, the Pittsburgh Formation becomes too deep for domestic water supplies in the central and western portions of Greene County. In Washington County, the average well yield is 1-gpm and it is necessary for most of the wells to be deeper than 100-ft below the ground surface (Newport 1973). Washington County's Uniontown and Pittsburgh Formations consist of largely impermeable fine grained shale; which is why the county's formations have low water-bearing capabilities. Much of the available water is stored in the fracture and joint system of the Uniontown and Pittsburgh Formations in Washington County.

The production of potable water from the geologic formations described above, not considering the alluvium formation, is largely dependent on the secondary permeability of the strata, particularly the region's sandstone layers. Fractures within these strata layers are natural conduits of groundwater that make it possible for water to move through the shallow aquifer system in the region. The secondary permeability tends to decrease by an order of magnitude as

the overburden increases every 100-ft (Stoner, Williams et al. 1987), which is why the majority of groundwater resources are within the first 200-ft of the ground surface.

The natural stress relief of valley systems also plays a role in the permeability of the strata in different topographic locations (i.e. hilltop, hillside, and valley bottom). As shown in Figure 3.1, natural stresses caused by compressional and tensile forces of the valley system induce fracturing in valley bottoms in the form of compression faults and valley walls in the form of tensile fracturing (Ferguson 1974). These natural fractures will lead to increased secondary permeability (Wyrick and Borchers 1981). The fracture density will be higher in valley bottoms and lower in hilltop locations, and because of this principle, the hilltop water supplies will tend to produce less water compared with valley bottom water supplies.



**Figure 3.1:** Natural valley stress relief fractures (Wyrick and Borchers 1981).

Aside from permeability, the hilltop water supplies are located in the recharge areas, and are dependent on water infiltrating into the ground after a precipitation event. Valley bottoms

are almost always areas of water discharge from groundwater sources or overland runoff. Water enters into the groundwater system through infiltration and flows from areas of high hydraulic head to low hydraulic head to eventually discharge into the valley bottom. As water travels downward through the strata it often encounters a stratigraphic layer of very low permeability, creating perched or semi-perched aquifer conditions. This impermeable layer impedes the water from percolating vertically, forcing the water to move laterally along the horizontal bedding plane to eventually discharge as a hillside spring or seep. These springs will exit the hillside where a fractured and permeable layer outcrops above an unfractured and impermeable layer.

Seasonal fluctuations in precipitation and infiltration rates can alter the amount of water circulating through the shallow aquifer system. Areas of recharge, or hilltop supplies, will see the greatest fluctuation of water levels during periods of low precipitation because the recharge water takes more time to reach the deeper hilltop supply levels as compared to valley bottom supplies levels. The discharges from hillside springs and water levels in wells less than 100-ft deep can see large production decreases during times of low precipitation (Stoner, Williams et al. 1987). However, springs lower on the hillside or in valley bottoms may prove more viable during times of low precipitation. Recharge rates are the highest between late fall and early spring, and during the growing season (April to September) much of the recharge potential is lost to evapotranspiration (evaporation and vegetation usage). Therefore, the groundwater levels are generally highest in late winter, and lowest in late summer. Nearly 40-percent (pct) of the average annual precipitation is lost to evapotranspiration throughout the year (Newport 1973).

The pre-mining hydrologic and geologic characteristics of the overburden strata, allow for the potential production of small to moderate residential supplies throughout the year in Greene and Washington Counties.

#### **4.0 LONGWALL MINING IMPACTS ON HYDROLOGY**

The overburden strata, in its pre-mining state, can produce adequate water supplies from the natural strata and its permeability. By creating a void in an underground setting the natural flow paths in the vicinity of the collapsed area have the potential to be altered. The elevation of the original water table and flow characteristics of the groundwater are susceptible to changes due to the overburden changes associated with subsidence. The alteration of overburden hydrologic characteristics can potentially result in the depletion or total loss of a water supply producing from the pre-mining production levels.

## 4.1 SUBSIDENCE THEORY

As briefly discussed in Section 1.0, longwall mining is a full extraction technique that allows controlled and immediate subsidence of the ground surface. As the coal is being mined, the roof support shields are advanced with the mining face, and the previously supported overburden is allowed to cave into the void behind the shields. This area of fractured strata is also known as the gob. Over the full extent of the panel, the shields advance many times leaving an area of gob of nearly the dimensions of the mined panel. This gob area is translated to the ground surface as a subsidence basin. Subsidence basins will range in size and depth depending on the panel dimensions, extraction thickness, and depth of overburden.

The basin can reach a point of maximum subsidence, or greatest vertical drop, when the critical panel width has been achieved (Peng 2008). If the actual panel width does not exceed the critical panel width, the subsidence basin is classified as a subcritical basin, and maximum subsidence is not achieved. The critical panel width, or short panel side, is linearly related to the overburden thickness, as shown in the equation:

$$W_c = 100 + 1.048 * h \quad (4-1)$$

where

$W_c$  = critical width, feet

$h$  = overburden thickness, feet

A point of maximum subsidence along the centerline of the panel, will be achieved when the actual panel width equals the critical panel width; also known as a critical subsidence basin. Once the critical panel width is surpassed by the actual panel width the subsidence basin is

considered a supercritical basin. A supercritical subsidence basin will reach the maximum subsidence and maintain the maximum value laterally over a large area in the base of the basin. Table 4.1 below provides a summary of the average panel widths, overburden, critical panel width, and subsidence basin classification for each of the seven longwall mines.

**Table 4.1:** Average panel widths, depths, critical panel widths, and classifications for each longwall mine.

Mine Name	Average Panel Width (ft)	Average Overburden Depth (ft)	Critical Width (ft)	Panel Classification
Bailey	1076	648	779	Supercritical Panels
Blacksville No. 2	1013	887	1030	Subcritical Panels
Cumberland	1183	739	874	Supercritical Panels
Emerald	1345	725	860	Supercritical Panels
Enlow Fork	1068	750	886	Supercritical Panels
High Quality	694	338	454	Supercritical Panels
Mine 84	1114	627	757	Supercritical Panels

The average longwall panels for six of the mines, except the Blacksville No. 2 mine, are supercritical in classification. The average overburden depth of the Blacksville No. 2 mine is deep enough that the actual panel width does not exceed the critical panel width which is why it is considered subcritical in nature.

The maximum possible subsidence ( $S_{max}$ ) for supercritical panels can be determined by the relationship:

$$S_{max} = m * a \quad (4-2)$$

where

$S_{max}$  = maximum possible subsidence depth, feet

$m$  = extraction thickness, feet

$a$  = subsidence factor, dimensionless

The subsidence factor can be represented by the equation (Peng 2008):

$$a = 0.6815519 * 0.9997398^h \quad (4-3)$$

where

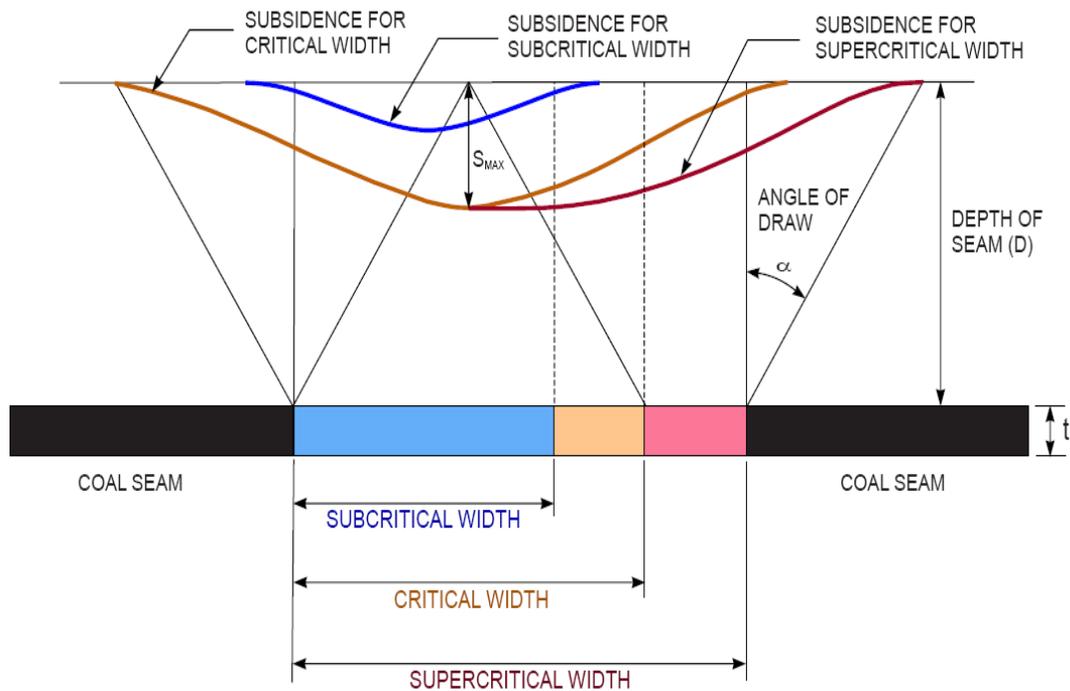
$a$  = subsidence factor, dimensionless

$h$  = overburden thickness, feet

The calculated average subsidence factor, based on the average overburdens for each mine (Table 4.1) is approximately 0.6 using Equation 4-3. An investigation on the effects of longwall subsidence on highways using actual subsidence measurements from Southwestern Pennsylvania longwall panels was conducted, and the average observed subsidence factor of these panels was approximately 0.66 (Gutiérrez 2010). Under the assumption that the average extraction height for each panel is 6-ft, the standardized  $S_{max}$  value for the typical longwall panel for this study is calculated to be between 3.5-ft to 4-ft.

Another relevant property of a subsidence basin is the angle of draw. This angle is measured from the vertical edge of the mined longwall panel to the point on the ground surface in which the subsidence basin is no longer present. Values of 10 to 25 degrees are typical values for the angle of draw in the Southwestern Pennsylvania's coal field (Society for Mining 1992).

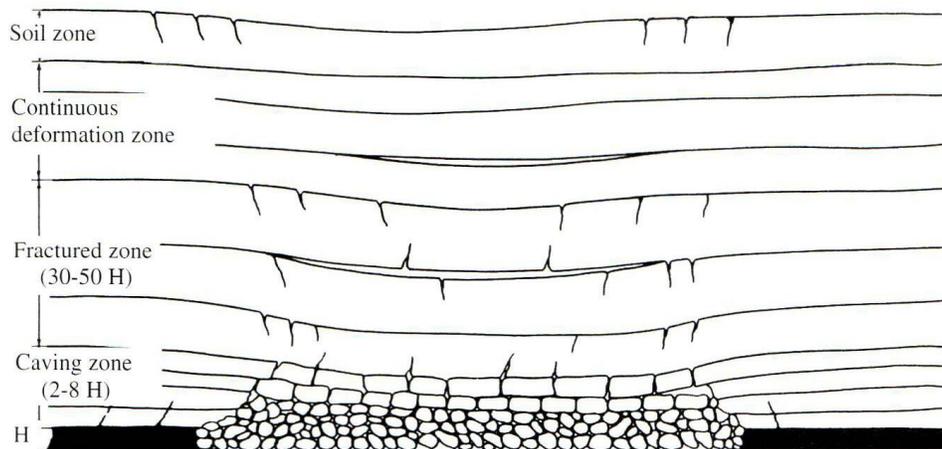
Figure 4.1 is a diagram that shows the properties and basin shapes of a subcritical, critical, and supercritical subsidence basin (D'Appolonia 2009).



**Figure 4.1:** A schematic showing the three subsidence basin types (D'Appolonia 2009).

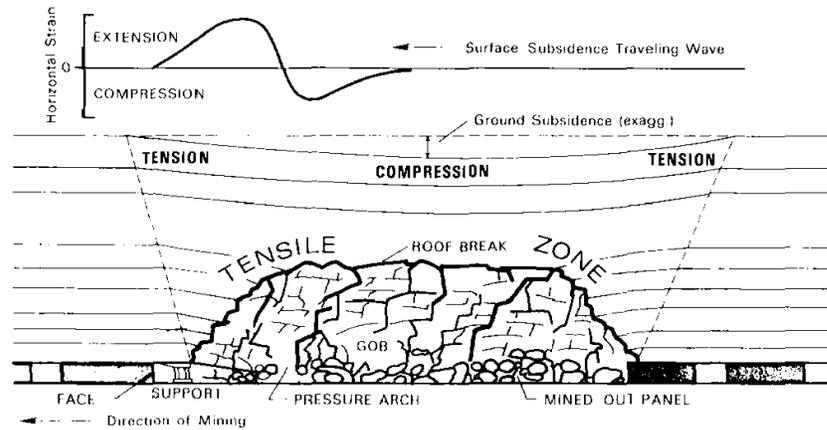
Subsidence propagation will cause the rock strata of the overburden to deform as well. This deformation results in portions of the strata between the mine elevation and the ground surface to fracture and displace. The subsided overburden strata are divided into four zones with differing degrees of fracturing (Peng 1992), as shown in Figure 4.2. The variances noted in the height of the zones are primarily due to the types of material comprising the strata. The zone closest to the mine void, called the caved zone, is where the roof rock caves irregularly into the mined out void. The height of this zone can be two to ten times the thickness of the mining height. Above the caved zone is the fractured zone where the strata are highly fractured, but remain stratified. This zone thickness can range between 28 to 52 times the mining height. The

next zone is called the continuous deformation zone where the strata bends and separates but does not fracture. The uppermost zone is known as the soil zone, where the basin intercepts the ground surface. It is possible for tension cracks to develop in this zone and propagate downward from the surface.



**Figure 4.2:** Depiction of the four subsidence zones (Peng 2008)

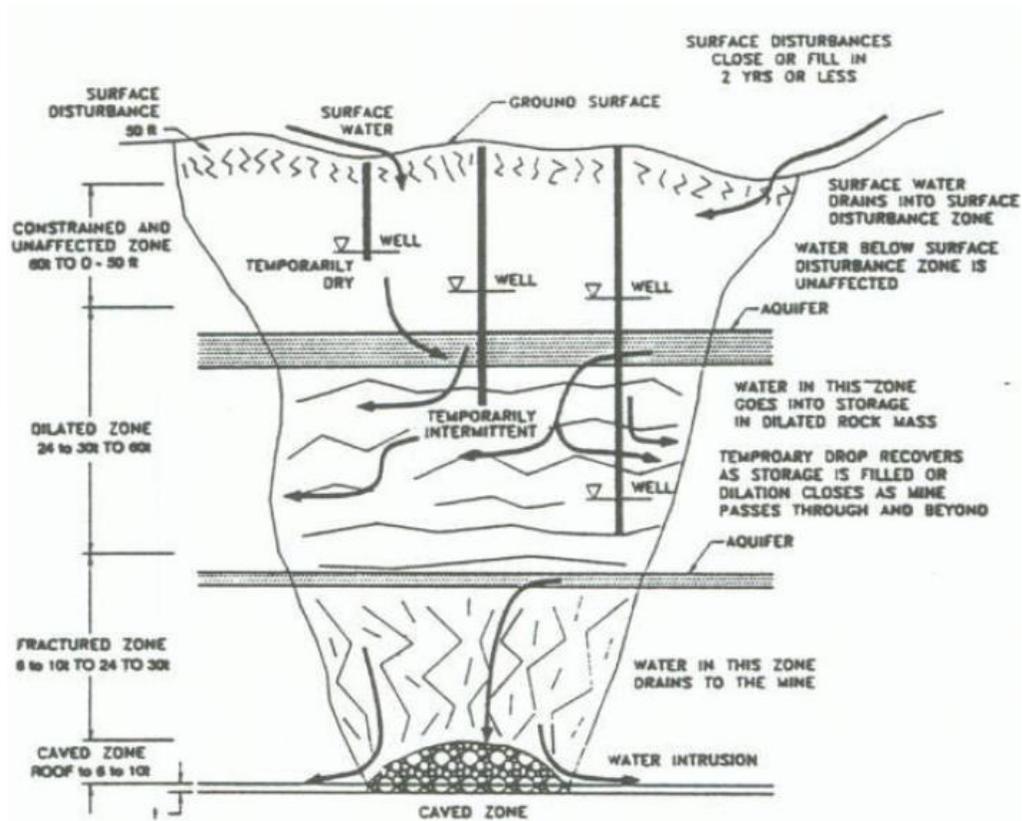
Regions of compressive and tensile stresses will also form as a result of the creation of a subsidence basin (Figure 4.3). Compressive stresses will cause the strata to shift laterally along the bedding planes or rupture in shear. These stresses can also open horizontal bedding planes and increase the lateral water movement, or create additional fractures when ruptured. Tensile stresses cause natural fractures to widen or new fractures to form, which can create new or larger vertical pathways for groundwater to move or be stored.



**Figure 4.3:** Zones of compression and tensile strata fracturing (Booth 1986)

The subsided overburden strata are divided into five zones based on their hydrologic responses to high extraction mining (Kendorski and Consultants 1993). These zones include (from mine to surface) a caved zone, fractured zone, dilated zone, constrained strata zone, and surface fracture zone. The caved zone is reported to be six to ten times the thickness of the extraction height and this zone is considered to be an area of complete hydrologic disruption. Above the caved zone is the fractured zone. The strata within the fractured zone contain vertically transmissive fractures, and the zone thickness can range between 24 to 30 times the extraction thickness. The next zone is called the dilated zone, and its characteristics include increased storativity with little or no vertical transmissivity. The dilated zone can range in thickness from 30 to 60 times the extraction height. If the mine is located deeper than the summation of the preceding zones thicknesses plus 50-ft for the surface fracture zone, there is a remaining intermediate zone of overburden called the constrained zone. Mining is reported to have little to no effect on the transmissivity or storativity of the strata in this zone. The uppermost zone is known as the surface fracture zone, and this is where the basin intercepts the ground surface, which can have vertically transmissive surface cracks. A common thickness of

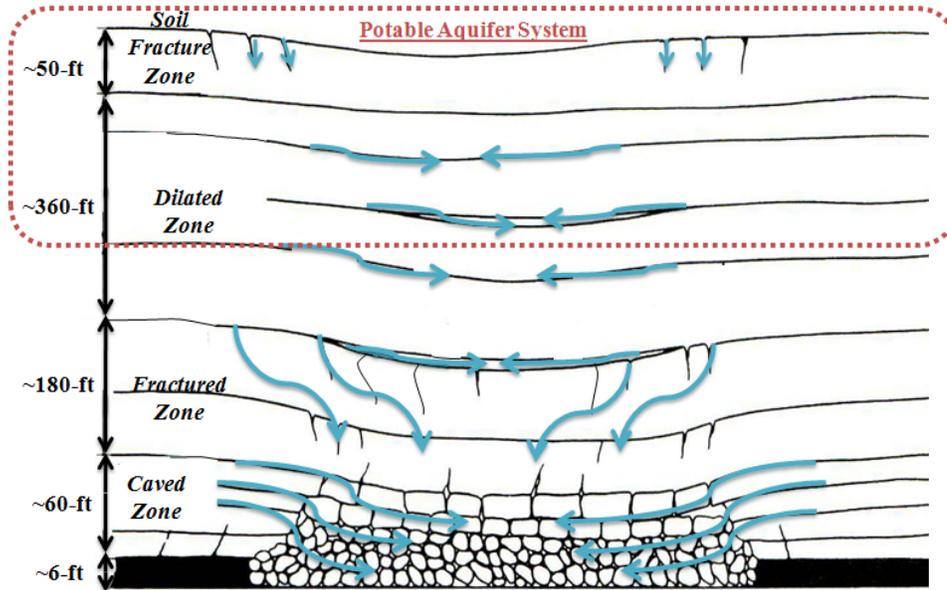
this zone is reported to be around 50-ft thick. A depiction of the five zones with their relative thicknesses and their hydrologic response descriptions is shown in Figure 4.4.



**Figure 4.4:** Hydrologic response zones (Kendorski and Consultants 1993)

Based on overburden response models by Peng (2008) and Kendorski and Consultants (1993), the expected hydrologic responses are controlled by overburden and extraction thicknesses. Shallow undermining results in a decreased distance from the mine void to the ground surface, which causes the subsidence zones of higher deformation and fracturing to be located nearer to the potable aquifer system (Peng 1992; Kendorski and Consultants 1993). Figure 4.5 presents a visualization of the possible hydrologic conditions that the potable aquifer

systems may be encountering at an average overburden depth of 650-ft and an extraction thickness of 6-ft, representative of this study.

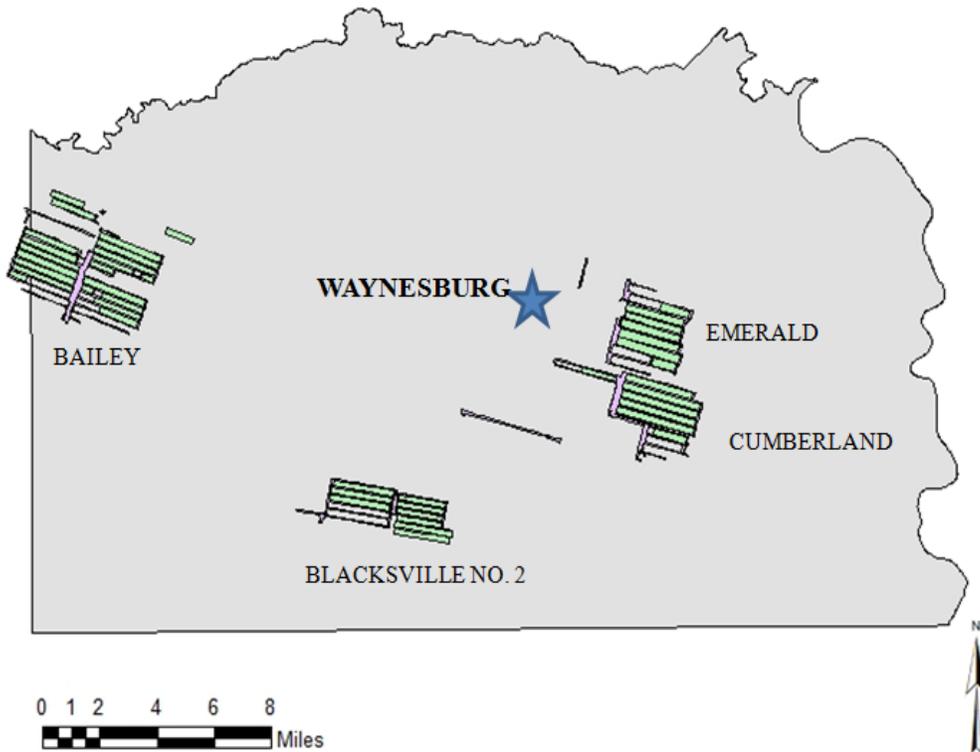


**Figure 4.5:** Average longwall panel's approximate hydrologic response zones; adapted from (Kendorski and Consultants 1993; Peng 2008).

As shown in Figure 4.5, the potable water supplies are generally drawing water from within the soil fracture zone and dilated zone which are associated with aquifer flow changes. Generally, the depth of overburden did not allow for the formation of a constrained zone, where little to no mining impact is generally observed. As the overburden depth increases a constrained zone between the dilated and soil fracture zone will develop, decreasing the likelihood that shallow aquifer groundwater levels would be altered by the dilated and fractured zones. Therefore, one would expect that as overburden thickness increases, the highly fractured strata would be located deeper underground, with the possible formation of a constrained zone, and an overall expectation of a decrease in the number of water supplies being impacted by mining.

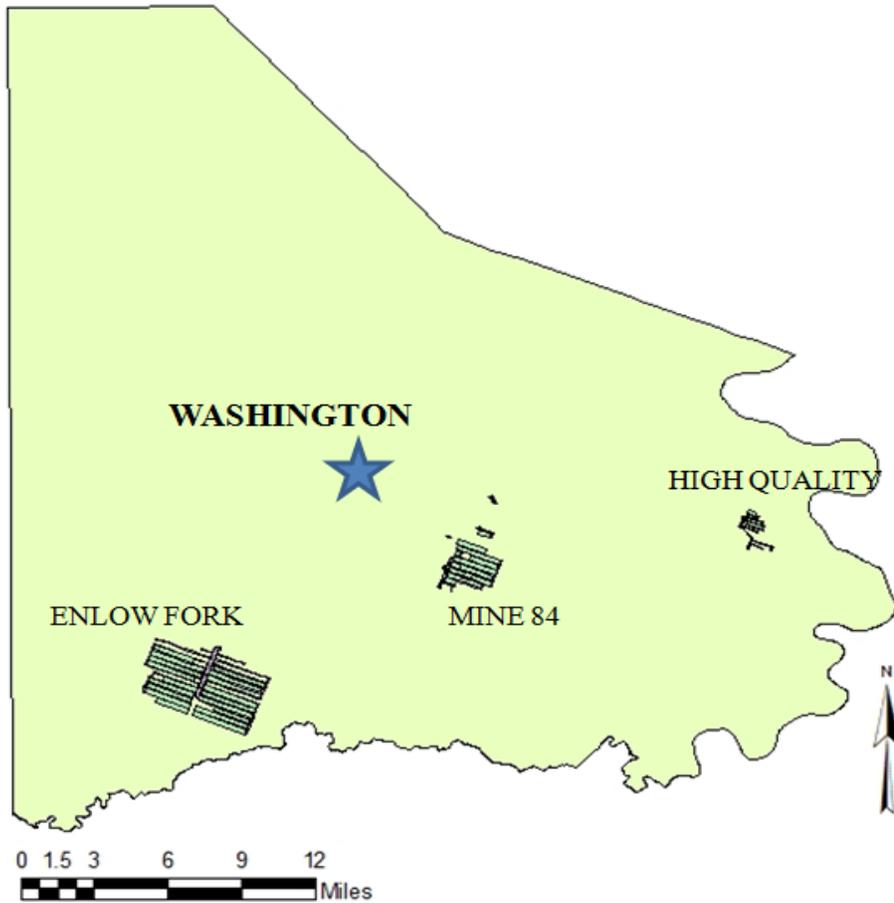
## 4.2 GREENE AND WASHINGTON COUNTY WATER SUPPLIES

There were four longwall mines that actively mined in Greene County between 2003 and 2008. Figure 4.6 shows the location of the four active mines of Greene County and the extent of mining over the five year period for each mine. Combined, these four longwall mines undermined approximately 15,700 acres in the five year period.



**Figure 4.6:** Greene County and the location of the four active mines of the study

There were three longwall mines that actively mined in Washington County between 2003 and 2008. Figure 4.7 shows the location of the three active mines of Washington County and the extent of mining over the five year period for each mine. Combined, these three longwall mines undermined approximately 8,800 acres in the five year period.



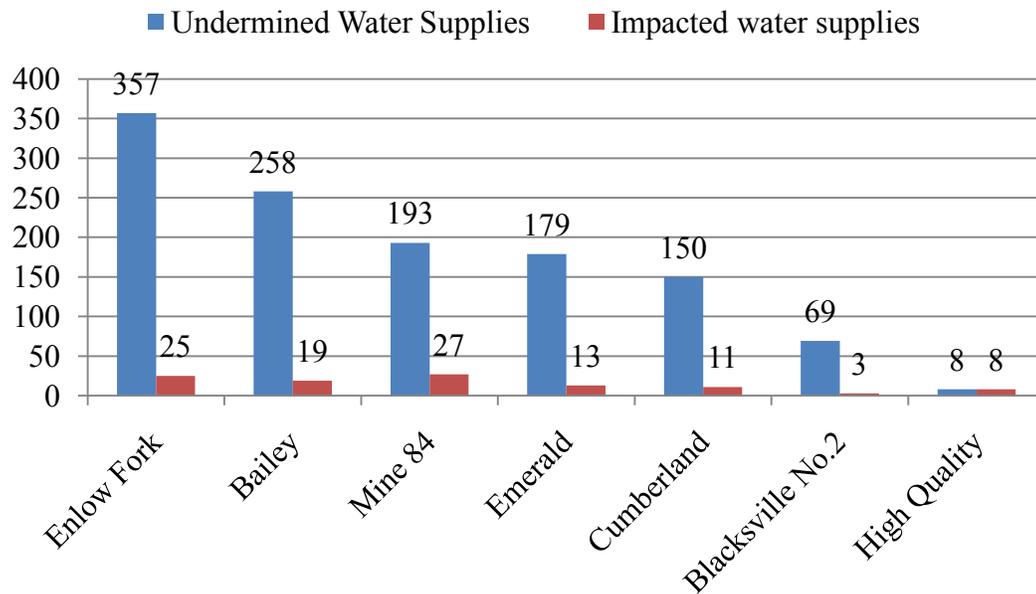
**Figure 4.7:** Washington County and the location of the three active mines of the study

Collectively, the seven longwall mines undermined 1,214 wells and springs. Table 4.2, provides a summary of the number of water supplies undermined by each of the seven mines. Of these 1,214 undermined water supplies, 106 of the supplies were identified and tracked as having had a water supply diminution or total loss attributed to longwall mining during the five year period; which is also shown in Table 4.2. A summary map for each mine depicting the locations of the undermined and impacted water supplies and the corresponding overburden values are provided in Appendix B.1.

**Table 4.2:** Total number of undermined and impacted water supplies per longwall mine

Mine Name	Water Supply Type		Undermined Water Supplies	Impacted Supplies
	Well	Spring		
Bailey	116	142	258	19
Blacksville No.2	44	25	69	3
Cumberland	77	73	150	11
Emerald	89	90	179	13
Enlow Fork	136	221	357	25
High Quality	1	7	8	8
Mine 84	106	87	193	27
Total	569	645	1214	106

Figure 4.8 shows a comparison between the total number of undermined water supplies compared to the total number of impacted supplies per mine.



**Figure 4.8:** Number of undermined (n=1,214) and impacted (n=106) water supplies

Based on the tables and figures shown, all of the mines impacted water supplies that it undermined. The percentages of impacted supplies are presented in Table 4.3. The maximum percentage of water supplies impacted is the High Quality Mine which impacted 100-percent of

its supplies; followed by Mine 84 with a 14-percent impact rate. Four of the mines, Bailey, Cumberland, Emerald, and Enlow Fork, impacted approximately 7-percent of the water supplies undermined. The minimum percentage of impacted water supplies is the Blacksville No. 2 Mine, with 4-percent of undermined supplies with impacts. Overall, 8.73-percent of undermined water supplies were impacted due to longwall mining from 2003 to 2008.

**Table 4.3:** Percentage of impacted water supplies by mine

Mine Name	Percent Impacted
High Quality	100.00
Mine 84	13.99
Bailey	7.36
Cumberland	7.33
Emerald	7.26
Enlow Fork	7.00
Blacksville No.2	4.35

Since each mine's water supplies reacted differently to the undermining process, as shown by the percentages of impacted supplies per mine, it is clear that there is variability in the hydrologic, geologic, and mining characteristics at each mine's location. Therefore, it is necessary to analyze the vulnerability characteristics of each water supply undermined by longwall mining. Trends in individual water supply hydrogeologic and mining settings will be analyzed in Section 5.0 to determine if particular characteristics will culminate into a water supply impact or a successful undermining.

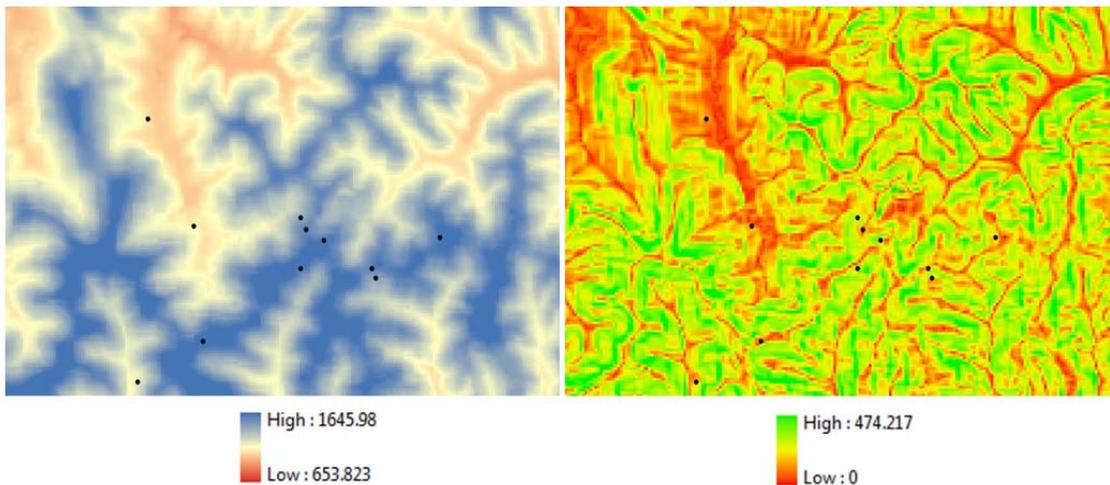
## **5.0 CHARACTERISTICS OF SUSCEPTIBILITY**

A reason for the large variance in percentages of impacts at several of the mines may be the result of certain mines undermining water supplies that are more characteristically susceptible to a water loss, based on the attributes of the water supply. Some of these factors pertain to their hydrogeologic setting, proximal location to mining, and timing at which each water supply was undermined. Using a portion of the ACT 54 assessment data (refer to Section 2.0 for data criteria), supporting literature, Module 8 of mine permit files, and the input of each water supply's characteristic attributes from the ArcGIS database, an analysis of an individual water supply's characteristic susceptibility is presented. The following subsections provide data to substantiate or refute the influence of these water supply settings on the likelihood of an impact.

## 5.1 HYDROGEOLOGIC SETTING

### 5.1.1 TOPOGRAPHY

The water supplies can be classified as being topographically located on a hilltop, hillside, or valley bottom. Hilltops and valley bottoms are low slope areas classified by their relative high and low topographic elevations, respectively. Hillside areas are areas of midrange elevations with high slope values (Figure 5.1).



**Figure 5.1:** Raster images for surface elevations (left) and slopes (right) used to classify water supplies

Many studies have reported differences in impact rates associated with a water supply's topographic location; with hilltop supplies being the most frequently impacted, followed by hillsides, and finally valley bottoms (Walker 1988; Leavitt and Gibbens 1992; Carver and Rauch 1994). The reasoning behind these results is most closely related to the recharge/discharge principles in a valley system. Valley bottoms supplies, located in discharge areas, will benefit from water recharge from upland areas; whereas hilltop supplies are dependent on recharge from

precipitation events. Table 5.1 presents the percentages of impacted supplies based on their topographic location.

**Table 5.1:** Number of water supplies unaffected and impacted based on their topographic location

Topographic Classification	Unaffected	Impacted	Percent Impacted
Hilltops	200	26	13.00
Hillsides	535	48	8.97
Valley Bottom	373	32	8.58

Approximately 13.0-percent of the undermined hilltop supplies were impacted; with hillsides and valley bottom supplies being impacted 9.0-percent and 8.6-percent, respectively. These results coincide with literature findings while demonstrating that hilltop water supplies may be more susceptible to even small groundwater elevation changes; whereas the valley bottom supplies are more likely to have an adequate quantity of water discharging into the valley area that any potential losses can be overcome. It is possible that the overburden disturbance may provide a connection from the higher groundwater elevations found with hilltop and hillside supplies, to deeper fracture systems of the valley bottom (Leavitt and Gibbens 1992).

### 5.1.2 OVERBURDEN

The average overburden for all seven longwall mines is approximately 687-ft with a standard deviation of 97-ft. For normally distributed data, such as longwall overburden, one standard deviation above and below 687-ft accounted for 2/3 of the data. Data in this range is considered

average for this study. Overburden values less than 590-ft are considered shallow and, conversely, greater than 784-ft are classified as deep.

Apart from Kendorski and Consultant’s hydrologic response model, several studies found that overburden thickness helps to determine the extent of aquifer system changes associated with high extraction mining. Strata dewatering was found to be limited to overburdens less than 700 feet (Tieman and Rauch 1987), and dewatering problems are greater when overburden values are less than 500-ft (Dixon and Rauch 1988; Parizek and Ramani 1996). Table 5.2 shows the percent of water supplies impacted based on their classification as shallow, average, and deep for this study.

**Table 5.2:** Number of water supplies unaffected and impacted based on their overburden classification

Overburden Classification	Unaffected	Impacted	Percent Impacted
Shallow	245	26	10.61
Average	640	57	8.91
Deep	223	23	10.31

Approximately 10.6-percent, 8.9-percent, and 10.3-percent of water supplies were impacted at shallow, average, and deep overburdens, respectively. The impact rate for deep supplies of 10.3-percent does not substantiate the results reported by other studies, but the large number of impacted hilltop supplies, nearly 60-percent, at deep overburdens, may play a role in the high impact rate for the deep supplies.

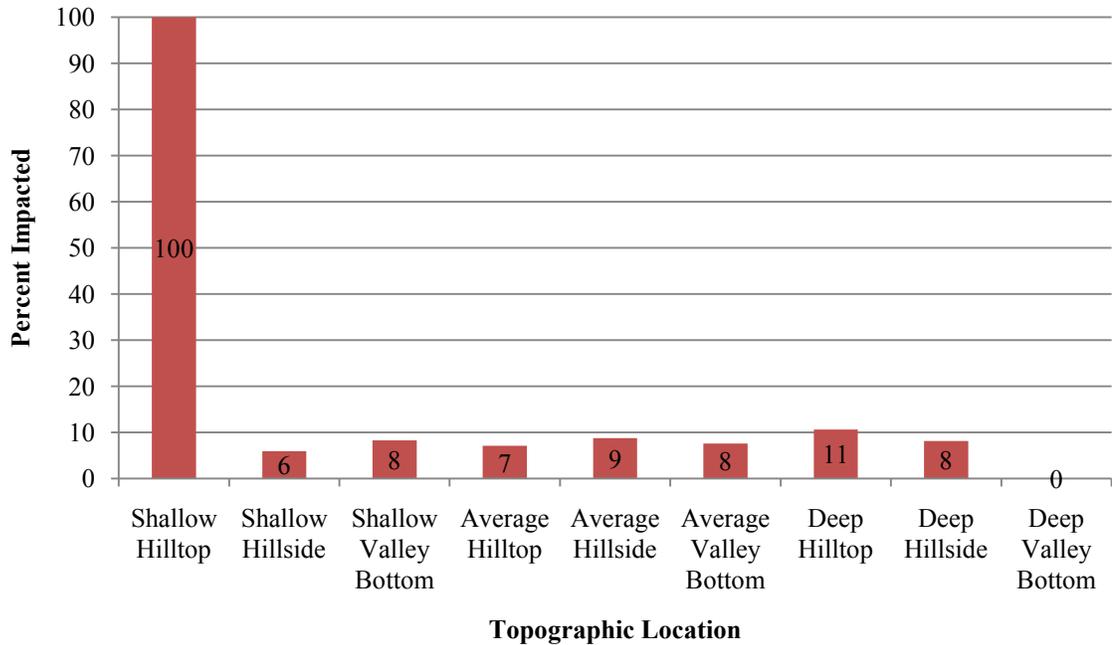
### 5.1.3 HYDROGEOLOGIC LOCATION SCENARIO

A combination of the water supplies' topographic and overburden classification is presented to determine if there are location scenarios that are more or less susceptibility to being undermined as shown in Table 5.3.

**Table 5.3:** Number of water supplies unaffected and impacted based on their location scenario

Depth	Topographic Location	Impact Category	
		Unaffected	Impacted
Shallow	Hilltop	0	6
	Hillside	79	5
	Valley Bottom	166	15
Average	Hilltop	91	7
	Hillside	343	33
	Valley Bottom	206	17
Deep	Hilltop	109	13
	Hillside	113	10
	Valley Bottom	1	0

It is not unusual to see the majority of impacted supplies being attributed to an average overburden depth because of the overburden normal distribution methodology. The potential susceptibility of a particular topographic location and overburden scenario was determined by relative percentages at each location scenario and shown in Figure 5.2.



**Figure 5.2:** Percentage of impacted water supplies based on location scenario.

As shown in Figure 5.2, the relative percentage of water supplies impacted at shallow hilltop locations is 100-percent, and conversely zero deep valley bottom water supplies were impacted. There was only one data point for the deep valley bottom supplies, so it is unclear if this percentage would be as low if there was a larger dataset at this location. The other topographic locations at differing overburdens show that an average of 92-percent of water supplies remained unaffected after undermining. Shallow hilltop water supplies are particularly susceptible to an impact due to undermining.

## 5.2 PROXIMAL LOCATION TO MINING

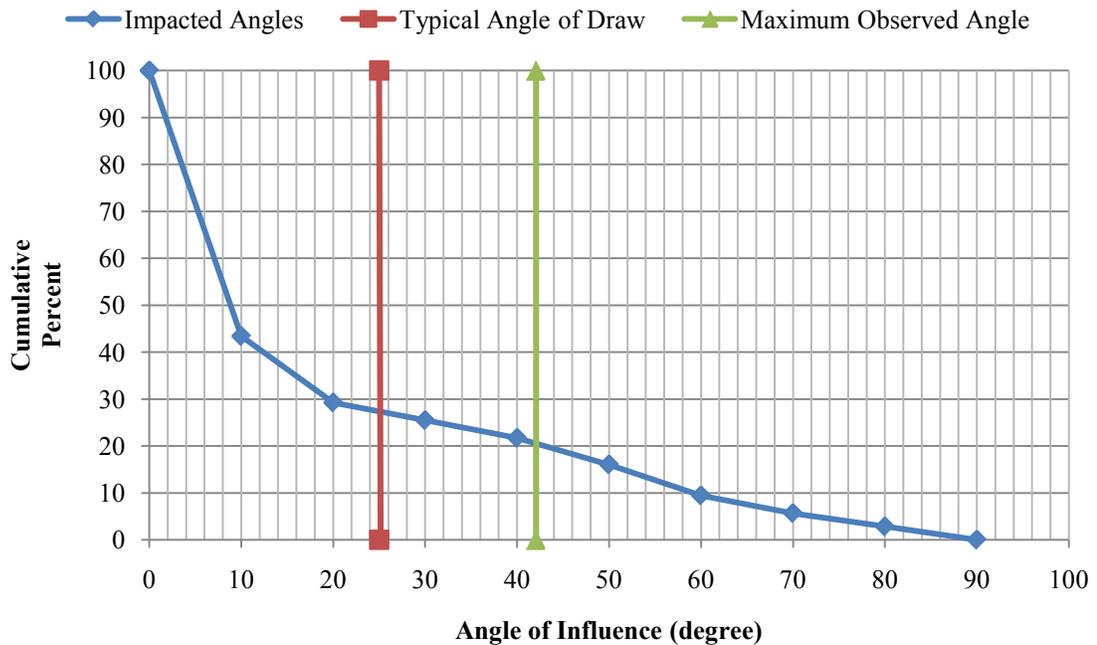
### 5.2.1 HYDROLOGIC ANGLE OF INFLUENCE

Acceptable values for the angle of draw for the coal fields of Southwestern Pennsylvania range from 10 to 25-degrees; however the extent of hydrologic changes may extend beyond the distance predicted by the angle of draw. Several studies reported maximum observed hydrologic angle of influence in Southwestern Pennsylvania's Pittsburgh coalbed of 27 to 38-degrees (Carver and Rauch 1994), 24-degrees (Moebis and Barton 1985), and 42-degrees (Tieman and Rauch 1987). The lateral distance between the water supply and the edge of the longwall panel was determined in the ArcGIS database. Using the overburden depth and the measured lateral distance, the angle of influence of the longwall panel to the water supply was determined using the following geometric relationship:

$$\text{Angle of Influence} = \arctan\left(\frac{\text{Lateral Distance}}{\text{Overburden}}\right) \quad (5-1)$$

The hydrologic angles of influence were calculated using the above equation for the impacted water supplies. The distribution of angles varied from zero-degrees, or directly over the longwall panel, to greater than 70-degrees. It is important to note that the water supplies were inventoried based on the PA DEP's regulatory standpoint that considers water supplies undermined if they are within 200-ft of any active mining, longwall or room-and-pillar mining methods. Therefore, it was not uncommon to see large angles of influence because the water

supply distances were measured to the nearest active longwall panel, not to the nearest mining. The distribution of angles of influence for impacted water supplies is shown in Figure 5.3.

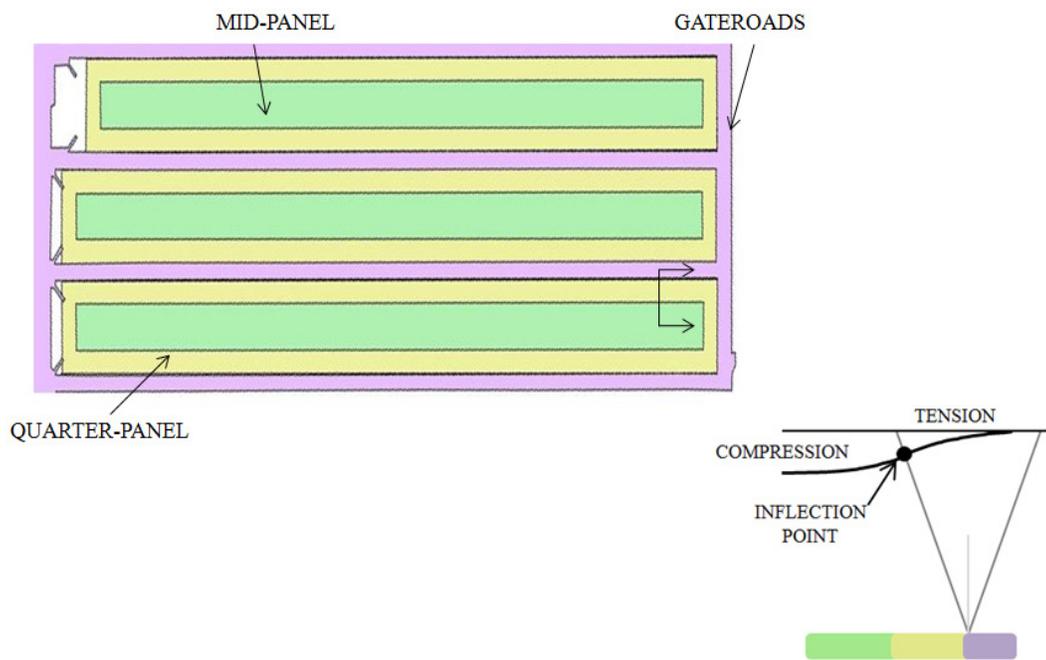


**Figure 5.3:** Distribution of angles of influence for impacted water supplies

Nearly 73-percent of the impacted supplies fall within the upper bound of the accepted Northern Appalachia angle of draw of 25-degrees (Society for Mining 1992). The remaining 27-percent of impacted supplies are outside of the 25-degree angle. Considering the largest observed angle of influence of 42-degrees, nearly 80-percent of the water supplies fall within the supported possible hydrologic angle of influence attributed to a longwall panel. It is possible that some of the water supplies largely outside of the longwall panel influence may have been affected hydrologically by room-and-pillar mining or were not directly located over active mining occurring during the assessment time period.

## 5.2.2 PANEL LOCATION

Longwall subsidence basins have zones of compression and tensile stresses (Figure 4.3). The compressive stresses are located in the flat portion of a supercritical subsidence basin, and extend laterally until the inflection point is reached. The inflection point is the point in which there is zero curvature, or the transition point from compressive to tensile stresses. A quarter-width buffer for each panel was created in ArcGIS, and this buffer separated the panel into a mid-panel (50-percent of the panel width) section for compressive stresses and quarter-panel (two outer 25-percent panel regions) section for tensile stresses (Figure 5.4).

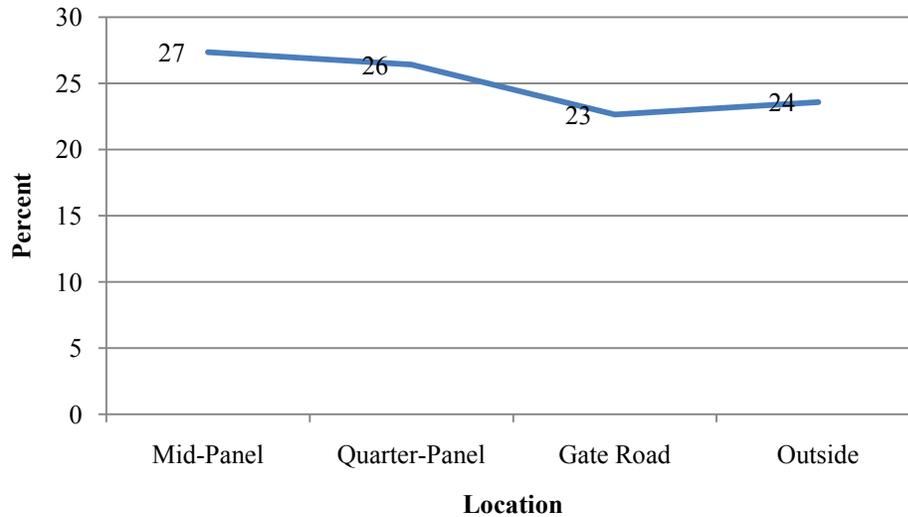


**Figure 5.4:** Panel classification locations and stress location cross-section

These regions provide a generalized depiction of the potential types of fracturing of the strata near the ground surface. The impacted water supplies were classified as mid-panel, quarter-panel, or if the supply was located outside of the panel it was classified as gateroad if over a room-and-pillar section, or as outside of active mining.

Several studies have reported observing water supplies located over the centerline of the longwall panel, or mid-panel region, to show the greatest water level fluctuations and head loss due to mining (Hill and Price 1983; Moebs and Barton 1985; Walker, Green et al. 1986; Tieman and Rauch 1987). This can most likely be attributed to the change from dynamic extensional strains and fracturing to static compressive strains or recompression of fractures in the mid-panel region of the subsidence basin. Water level fluctuations begin approximately when the ground surface is subjected to tensile strains, and maximum rate of water loss and lowest water levels corresponded to the point of maximum tensile ground strains; water levels began to recover once the point of maximum compressional strain was achieved (Trevits and Matetic 1991). The point of maximum compressional strain is most likely attributed to the closure or reduction of extensional fractures. Correspondingly, water supplies located over room-and-pillar sections and outside of active mining showed little negative effects of mining (Hill and Price 1983; Moebs and Barton 1985; Carver and Rauch 1994). Therefore as the distance from the mid-panel increases, the stresses on the overburden decrease (Walker 1988).

The percentage of impacted supplies according to their panel location is calculated and shown in Figure 5.5.



**Figure 5.5:** Percentage of impacted water supplies at each longwall panel location.

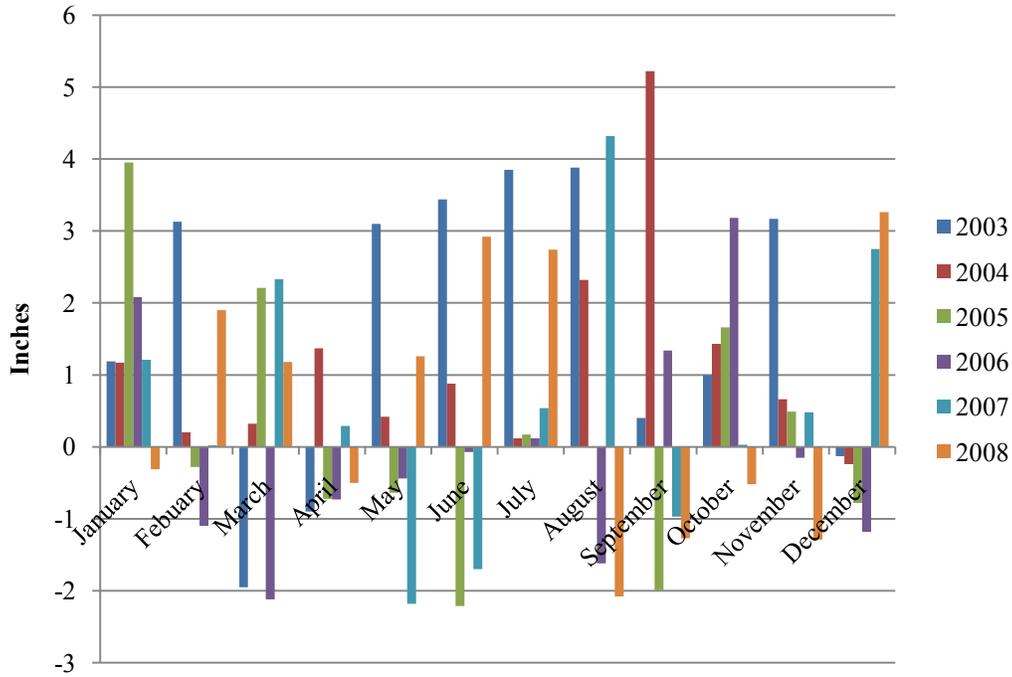
Water supplies located directly over mined longwall panels accounted for 27-percent and 26-percent of the impacted water supplies, based on their location over the mid-panel and quarter-panel regions, respectively; while gateroad and outside of active mining locations accounted for 23-percent and 24-percent of the impacts, respectively. Due to the formation of a subsidence basin directly over the mined panel, the expectation of an impact is greater over the panel, and less likely as the distance between the water supply and the longwall panel increases. This principle is affirmed in the figure, but not overwhelmingly.

### **5.3 CLIMATIC CONDITIONS AT TIME OF IMPACT**

The date of the water supply impact was referenced to determine if undermining a water supply during times of below average precipitation or during the months of low groundwater infiltration translates to more water supplies being impacted by mining. No literature reporting on this concept was found, but it is hypothesized that impacts rates may be higher when a water supply is undermined in times of below average precipitation and during the growing season because there is less water recharging the aquifer system.

#### **5.3.1 LONG-TERM AVERAGE PRECIPITATION RATES**

The daily precipitation totals for the duration of the assessment period were collected from Waynesburg Wastewater Treatment Facility. The daily totals were summed to calculate monthly totals during the five year assessment time period. The monthly totals for the years 2003 to 2008 were compared to the long term average precipitation rates for each month for Waynesburg, Pennsylvania (Figure 5.6). The long-term average values were collected from the *Weatherbase* website (Associates 1997).



**Figure 5.6:** Precipitation totals compared to the long-term precipitation averages for Waynesburg

The below average precipitation months include: December 2003 and 2004; February, April, May, June, September, and December of 2005; February through June, August, November, and December of 2006; May, June, and September of 2007; and January, April, and August of 2008. The months of the assessment period have been compared to the distribution of the impacted water supplies, as shown in Table 5.4.

**Table 5.4:** Number of impacted water supplies (n=106) tabulated by month of occurrence.

Date:	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
2003								0	0	7	2	<u>1</u>
2004	0	1	0	2	1	0	6	2	1	0	1	<u>0</u>
2005	0	<u>1</u>	0	<u>0</u>	<u>1</u>	<u>3</u>	1	2	<u>5</u>	3	3	<u>0</u>
2006	0	<u>0</u>	<u>3</u>	<u>25</u>	<u>4</u>	<u>2</u>	2	<u>0</u>	1	0	<u>1</u>	<u>2</u>
2007	0	0	0	0	<u>1</u>	<u>0</u>	0	0	<u>1</u>	2	4	12
2008	<u>1</u>	1	0	<u>1</u>	0	0	0	<u>0</u>				

\* Above Average Precipitation

\*\* Below Average Precipitation

As shown in Table 5.4, there were a total of 106 impacted water supplies; with 52 occurring in below average precipitation months and 54 occurring in at or above normal precipitation months. There were 22 months of below average and 39 of normal or above normal precipitation. By dividing the number of impacted water supplies by number of months for each precipitation condition, there was an average of 2.36 supplies impacted per below average month and 1.38 supplies impacted for above the average or normal precipitation months. Water supplies appear to be between 1.5 to 2 times more likely to be impacted where below average precipitation coincides with longwall undermining.

### **5.3.2 SEASONAL INFILTRATION RATES**

The total number of impacted water supplies is categorized based on the month of undermining to determine if the natural infiltration rates, based on seasonal climatic conditions can result in higher rates of water supply impacts (Table 5.5). The months January, February, March, October, November, and December are considered months of low evapotranspiration and therefore times of high groundwater recharge. Conversely, months April through September will have high rates of evapotranspiration, because of vegetation usage, and therefore lower rates of groundwater infiltration.

**Table 5.5:** Number of water supplies impacted based on month of undermining; left side- high groundwater recharge months and right side- months with high rates of evapotranspiration

High Groundwater Recharge		High Evapotranspiration Rate	
Month	Number of Impacts	Month	Number of Impacts
January	1	April	28
February	3	May	7
March	3	June	5
October	12	July	9
November	11	August	4
December	15	September	8
Total	45	Total	61

Nearly 58-percent of the water supply impacts occurred during months of low groundwater infiltration, as compared to the 42-percent of impacts occurring during months of high groundwater infiltration. Undermining during times of low groundwater infiltration rates may also influence how groundwater reacts to undermining.

## 5.4 MINE INFLOW

The mine inflow records for the seven longwall mines were collected by referencing the Module 8 permit files for each mine. Mine inflow rates are estimated by the rate at which water is pumped out of a mine. The water infiltrating into the mine can be moving in from the groundwater system above the mine, or from nearby abandoned and flooded mines. Groundwater will move by gravity or from pressure areas of high hydraulic head to areas of low hydraulic head. The mine inflow rates were converted into gallons per minute per acre, and shown in the Table 5.6. The value for Blacksville No.2 was not determined because discharges from the mine occur in West Virginia.

**Table 5.6:** The mine inflow rates (rates of pumping required) for each longwall mine.

Mine Name	Inflow (gpm/acre)
Bailey	0.032
Blacksville No. 2	n/a
Cumberland	0.250
Emerald	0.130
Enlow Fork	0.005
High Quality	0.480
Mine 84	0.036

Groundwater will only drain to the underground mine from the shallow aquifer system if they are hydraulically connected via the fractured strata (Booth 1986). As shown in Figure 4.4, a dilated zone of increased storativity with little or no vertical transmissivity (Kendorski and Consultants 1993). This zone is defined as the layer that prevents large amounts of surface and groundwater intrusion into the mine from above. The two layers below this layer are the fractured and caved zones, which account for approximately 30 times the thickness of mining.

In order for the shallow aquifer system to infiltrate into the mine, with a mining height of 6-ft, the shallow aquifer system would predictably need to be within 180-ft of the mine to hydraulically connect the shallow aquifer system directly with the mine. The overburden of the longwall mining that occurred during the assessment period was greater than 180-ft deep; therefore little infiltration of the shallow aquifer system was expected.

## 5.5 RESOLUTIONS TO IMPACTS

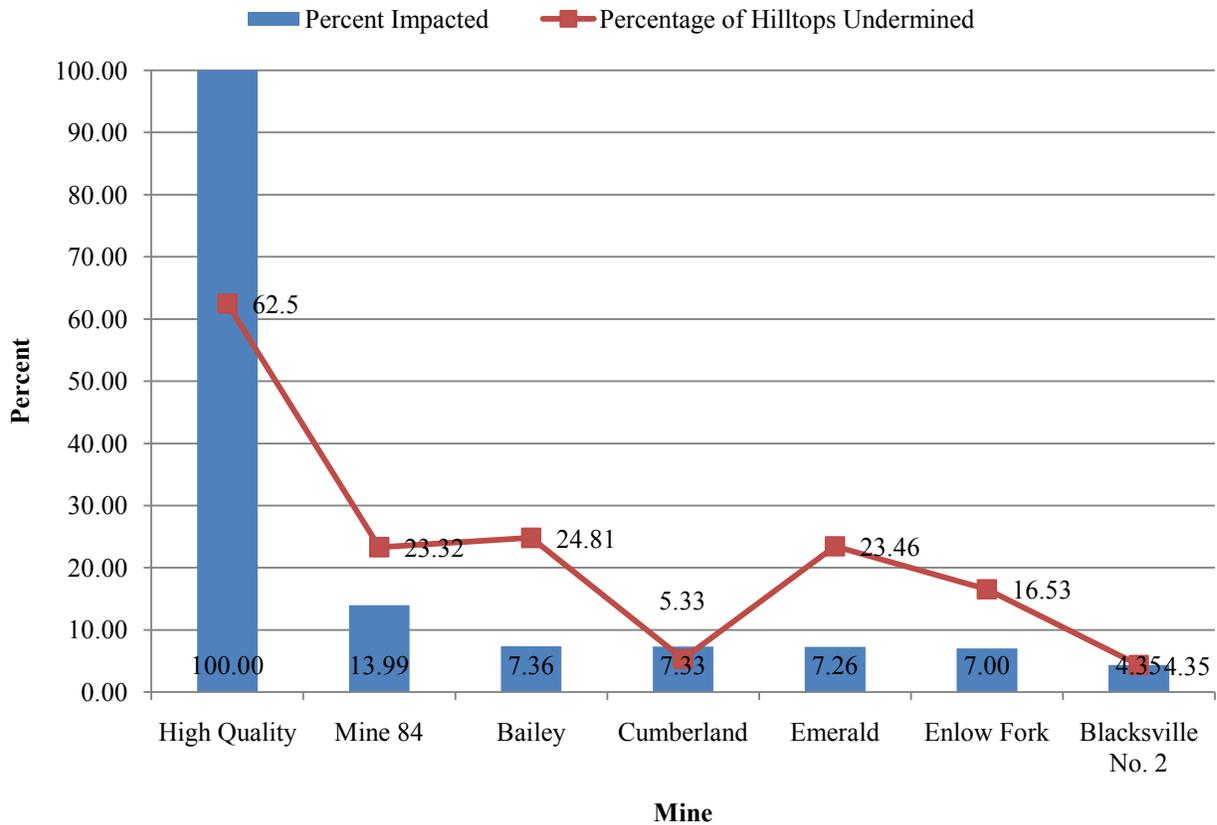
The PA DEP ensures that if a water supply is impaired by mining that the property owner is provided with a replacement water supply that was at the pre-mining water quantity and quality, a buyout, or compensation for the loss. Of the 106 impacted water supplies, 69 of the impacted supply claims were settled by a buyout, compensation, or by an agreement; 11 received a replacement supply in the form of public water; and 26 of the supplies were replaced with new supplies or the existing supplies recovered post-mining. Because of private contractual agreements it is not possible to determine what actions were taken or how the supply was replaced when an agreement was used to finalize an impact. A water supply may be replaced with public water if that is the most convenient and economical option for the replacement; therefore, the condition of the impacted well or spring post-mining is generally unknown. Resolutions stating that the water supply was replaced with another well or spring, or that the water supply recovered post-mining, indicate adequate water supplies can still be produced from the shallow aquifer system post-mining.

## **6.0 UNDERMINING CHARACTERISTICS BY MINE**

Section 5.0 presents trends in the data for individual water supply characteristics. It is important to apply these trends to each of the seven mines to determine if the individual mines undermined a certain characteristically susceptible water supply more or less frequently, compared with their water supply impact rates. As presented in Table 4.3, the impact rates at each of the seven longwall mines varied greatly. The High Quality mine impacted 100-percent of its supplies, followed by Mine 84 with a 14-percent impact rate, and the lowest impact rate attributed to the Blacksville No.2 mine with 4.4-percent of undermined water supplies impacted. The remaining four longwall mines, Bailey, Cumberland, Emerald, and Enlow Fork all impacted approximately 7-percent of the water supplies undermined. The trends chosen for additional analysis for each individual mine include percentage of hilltop supplies undermined, depth to mining, and percentage of supplies located over the longwall panel.

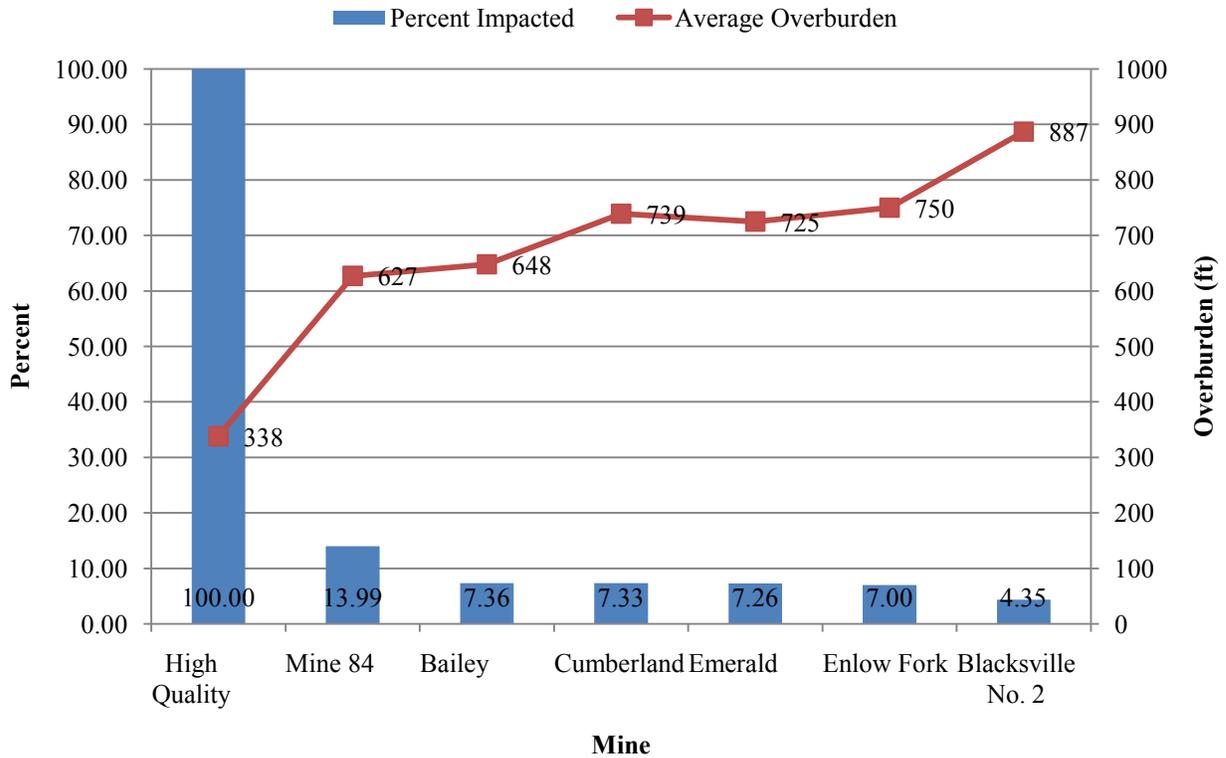
As discussed in Section 5.1, the topographic location of a water supply directly influences the likelihood of an impact due to mining. Hilltop supplies were impacted more frequently, at 13.0-percent, whereas hillsides and valley bottoms were impacted 9.0-percent and 8.6-percent, respectively. Because hilltop supply locations are more likely to be impacted, the percent of hilltop supplies undermined by each mine was determined and compared to the impact rates to determine if undermining hilltop water supplies more frequently has an effect on the mine impact rates (Figure 6.1). As shown, there does not seem to be an overwhelming

relationship between undermining a large number of hilltop supplies and the overall water supply impact rates.



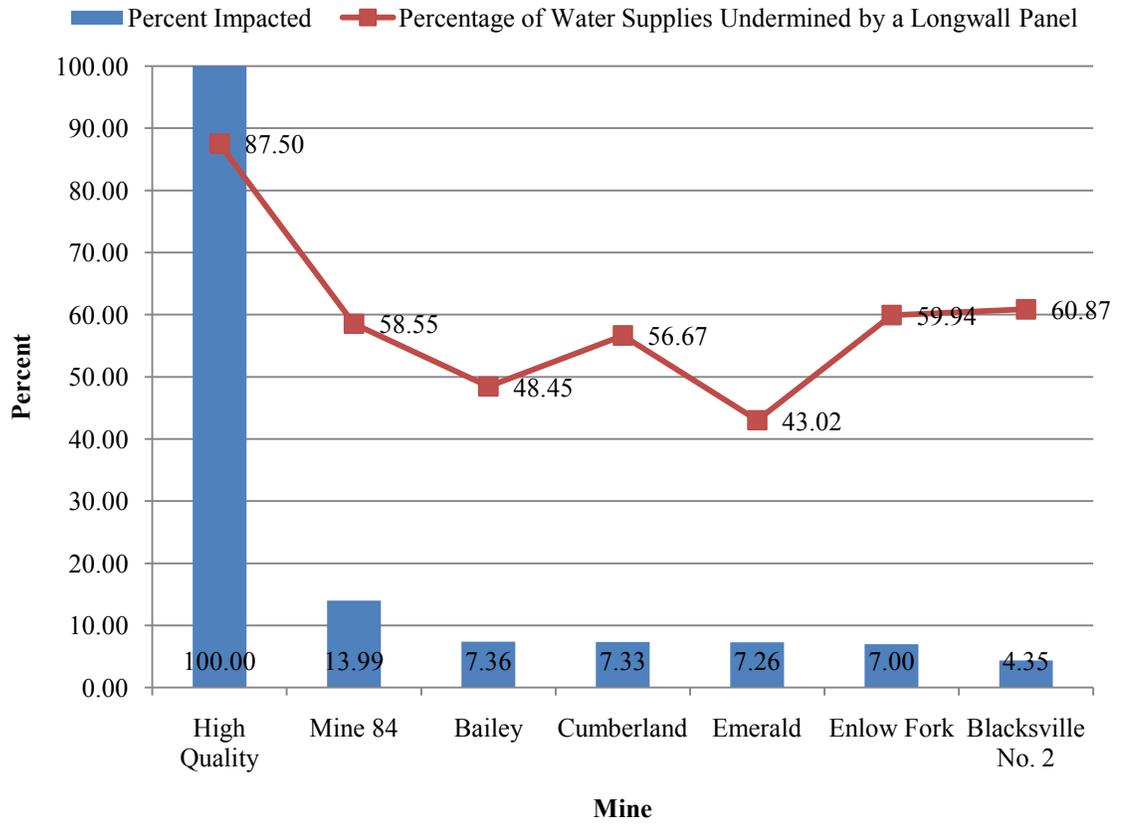
**Figure 6.1:** Mine impact rates compared to percentage of hilltop supplies undermined by mine

The next trend for comparison is average depth to mining for each of the mines. The average overburdens for each mine are presented in Table 4.1, and the values range from a minimum of 338-ft at the High Quality mine to a maximum of 887-ft at the Blacksville No. 2 mine. As shown in Figure 6.2, there is a direct relationship between overburden thickness and the percent of impacted water supplies (i.e. as overburden thicknesses increase, the impact rates decrease).



**Figure 6.2:** Mine impact rates compared to average overburden of the mine

Water supplies located directly over a longwall panel accounted for a majority of the impacted water supplies. The percentage of water supplies undermined by a longwall panel, either mid or quarter-panel locations, at each mine was determined and compared with the water supply impact rate for the mine (Figure 6.3). There does not seem to be any relationship to frequency of supplies being directly undermined by a longwall panel, and impacts rates of the mines.



**Figure 6.3:** Mine impact rates compared to percentage of water supplies undermined by a longwall panel

## 7.0 SUMMARY

There were seven longwall mines in operation in Greene and Washington County between the years of 2003 and 2008. These seven mines undermined 24,535 acres and a total of 1,214 wells and springs. Water supplies impacted by mining, either by water supply diminution or total loss of supply, accounted for 106 out of the 1,214 undermined supplies; therefore, 8.7-percent of water supplies within 200-ft of active mining were impacted. The water supplies undermined by each of the seven mines varied in response to being undermined at each mine site, between 100 percent (High Quality Mine) and 4.35 percent (Blacksville No. 2 Mine).

Based on the characteristic attributes of the impacted supplies, potential susceptibility characteristics were analyzed with the purpose of assessing water supply vulnerability to being undermined by longwall mines. The following susceptibility characteristics were analyzed:

- *Hydrogeologic Setting:*
  - Hilltops were confirmed to be more susceptible to longwall mining; particularly shallow hilltops.
  - Individual water supply overburden impact rates did not verify previous observations that deeper overburden reduces likelihood of impact.
- *Proximal Location to Mining:*
  - *Hydrologic Angle of Influence:* 80-percent of water supplies were within maximum observed hydrologic angle of influence of 42 degrees

- *Longwall Panel Location:* Longwall panel location impact rates did not overwhelmingly support previous observations that impacts are much higher over the panel and decrease as distance away from panel center increases.
- *Climatic Conditions at Time of Impact:*
  - *Long-Term Average Precipitation Rates:* Water supply impacts were 1.5 to 2 times more likely to occur during months of below average precipitation in conjunction with undermining.
  - *Seasonal Infiltration Rates:* Nearly 60-percent of water supply impacts occurred during the growing season when much of the groundwater infiltration is lost to evapotranspiration.
- *Mine Inflow:* There were no indications to suggest that the shallow aquifer system is being lost to mine inflow. Generally, overburden values are not shallow enough to hydraulically connect the shallow aquifer system directly with the mine.

The water supplies undermined by each of the seven mines varied in response to being undermined at each mine site. The water supply impact rates were most closely related with the average overburden thickness between the mine and the ground surface. The mines located deeper underground had overall lower impact rates compared with mines with less overburden between the mine and the ground surface.

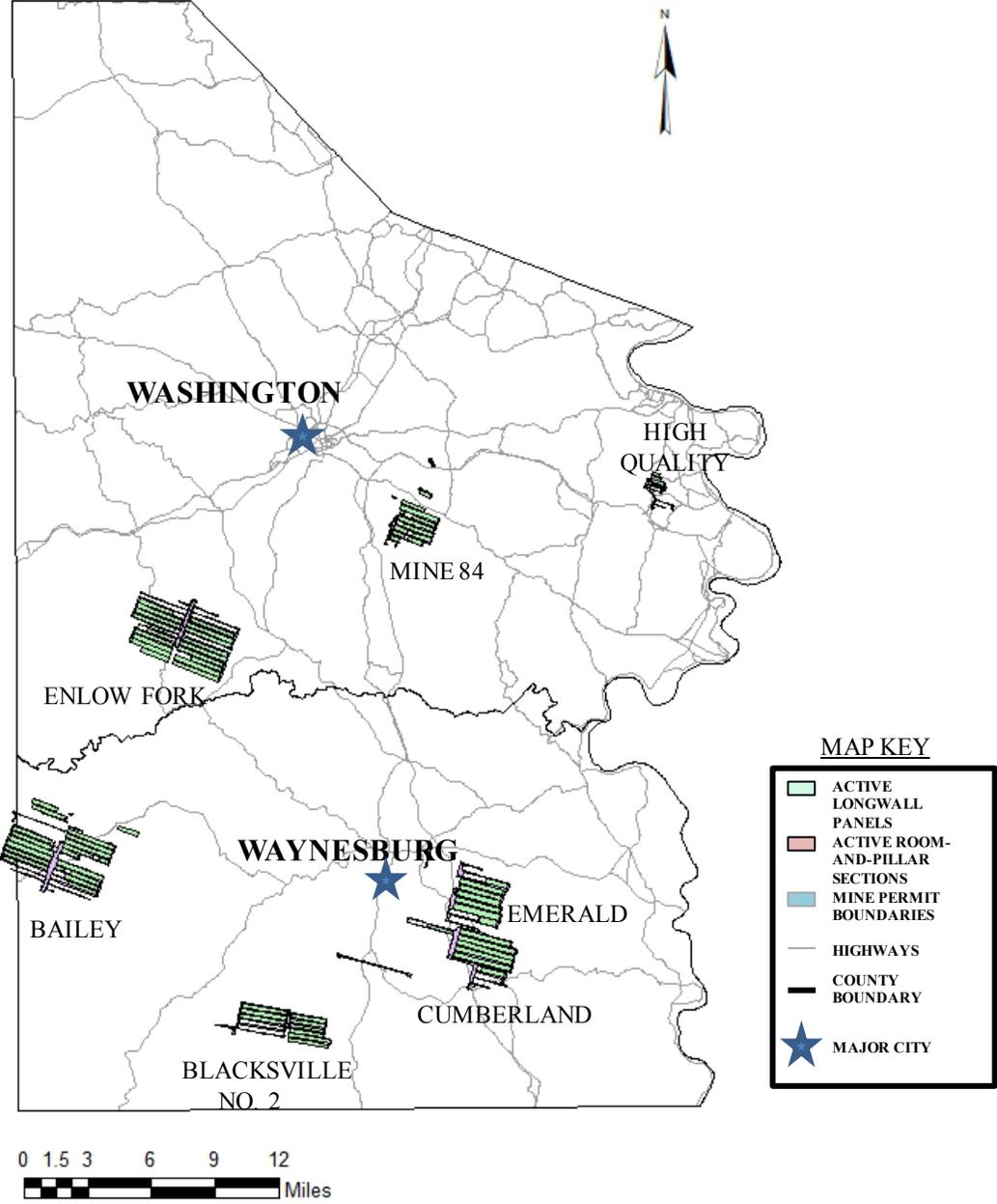
## **8.0 CONCLUSION**

The purpose of this study was to investigate the hydrogeologic changes to overburden strata due to longwall coal mining and the effect of the changes on potable water supplies producing from the strata of Southwestern, Pennsylvania. Understanding the hydrogeologic changes is useful when attempting to predict if diminution or total loss in supply will occur when active longwall mining is in the vicinity of the potable aquifer systems. Hydrologic response models based solely on overburden thickness may indicate an overall trend at each mine site, but may not be useful for predicting potential supply impacts on a case by case basis. In order to fully analyze and predict potential impacts by longwall mine subsidence to the hydrogeology, it is imperative to consider many factors including hydrogeologic setting, proximal location to mining, and climatic conditions at time of undermining.

## **APPENDIX A**

### **A.1 MAP OF EXTENT OF LONGWALL MINING (2003-2008)**

# EXTENT OF MINING FOR GREENE AND WASHINGTON COUNTIES (2003-2008)

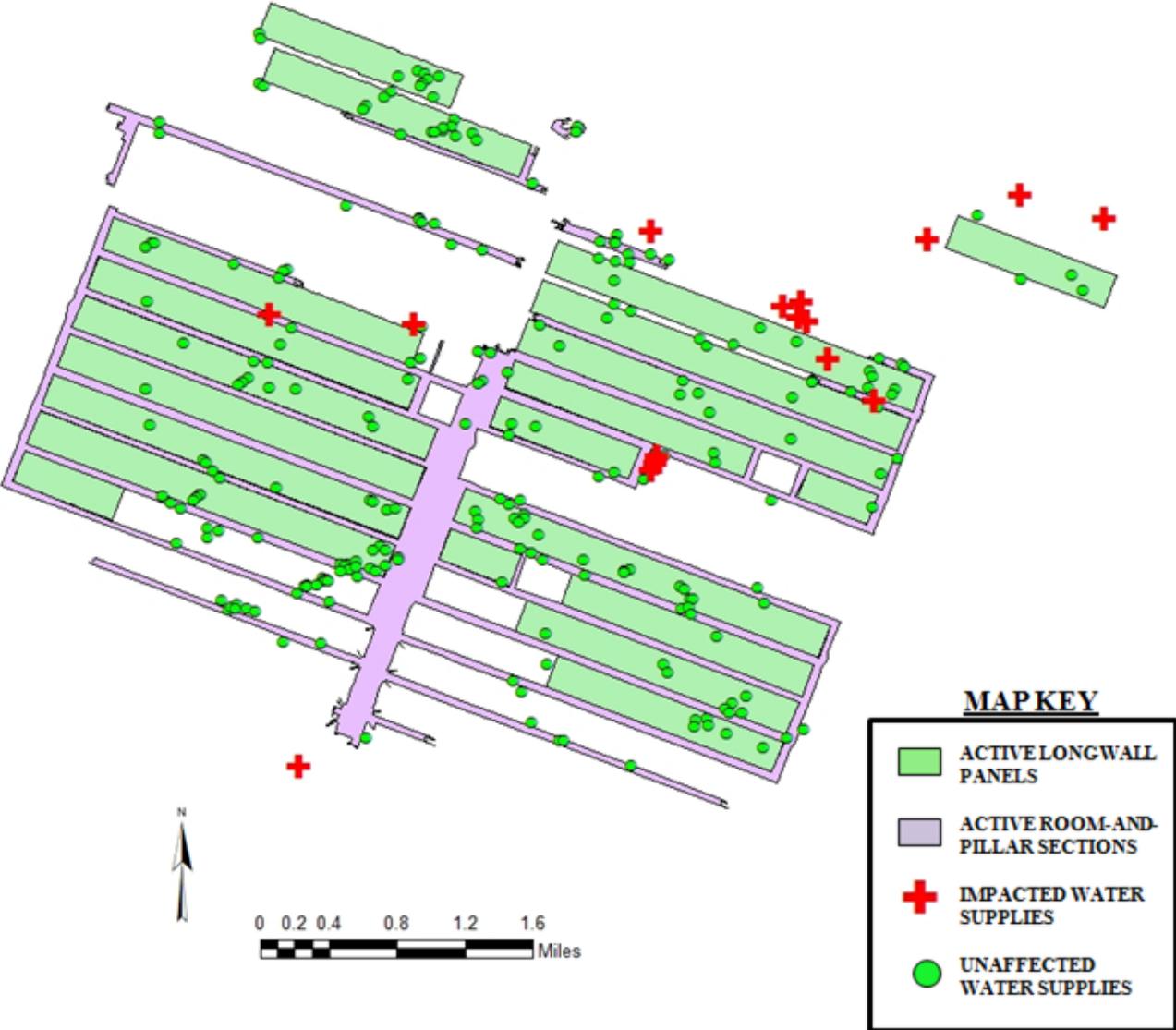


## **APPENDIX B**

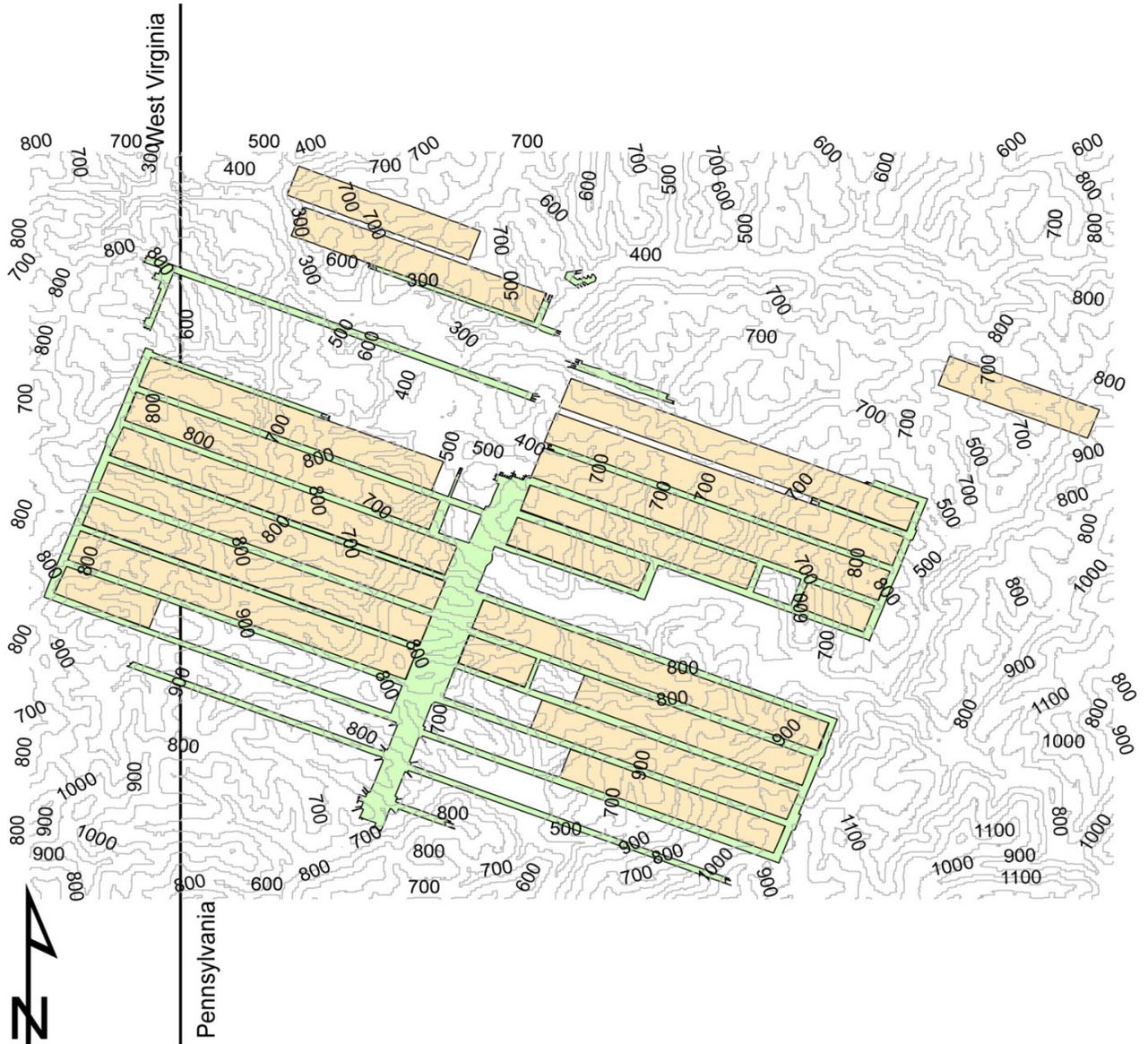
### **B.1 WATER SUPPLIES AND OVERBURDENS PER MINE**

The following maps provide the extent of mining during the five year assessment, as well as the location of the undermined water supplies. The water supplies that are symbolized as a green circle are the supplies that were not affected by mining. The red crosses symbolize the undermined water supplies that were impacted by mining. The appendix also contains additional maps detailing the overburdens at each of the mine sites.

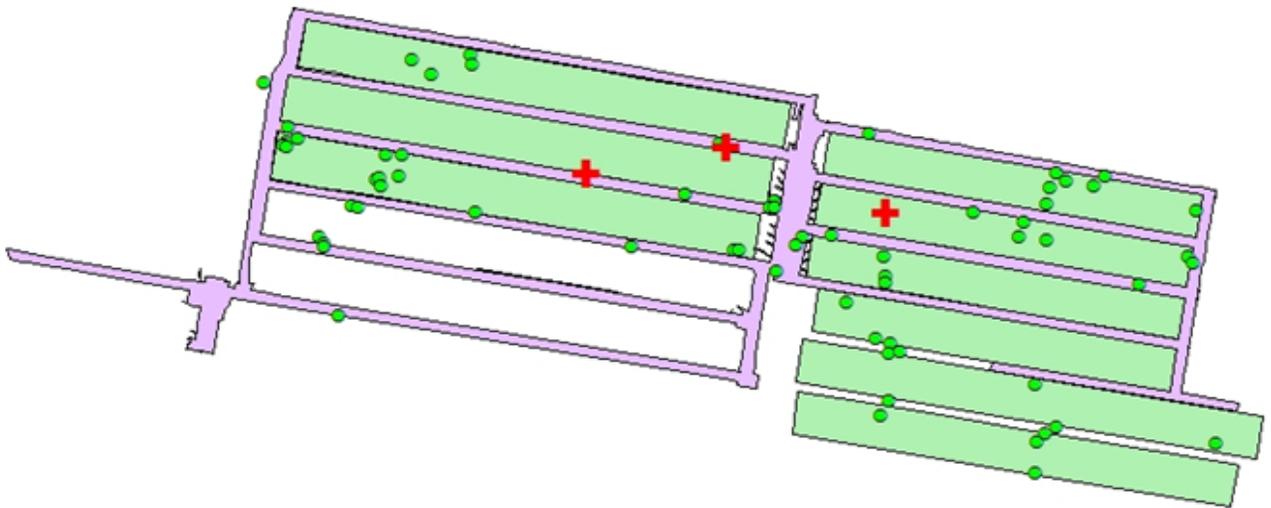
# BAILEY MINE WATER SUPPLIES



# BAILEY MINE OVERBURDEN



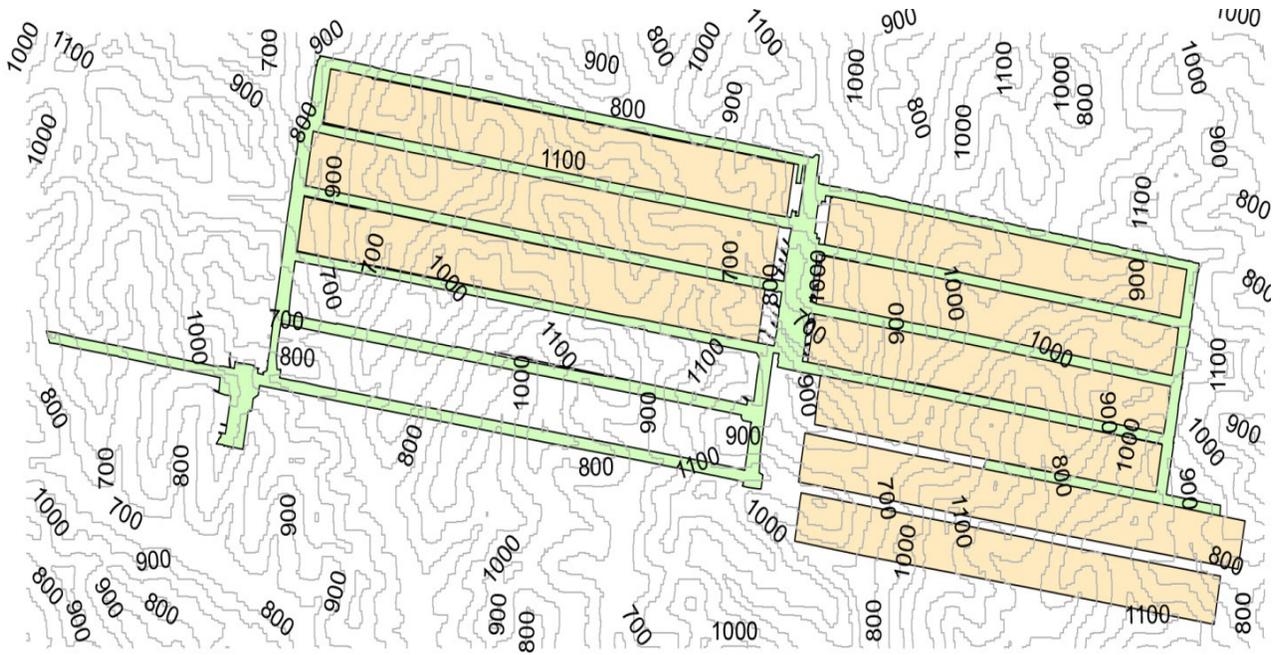
# BLACKSVILLE NO. 2 MINE WATER SUPPLIES



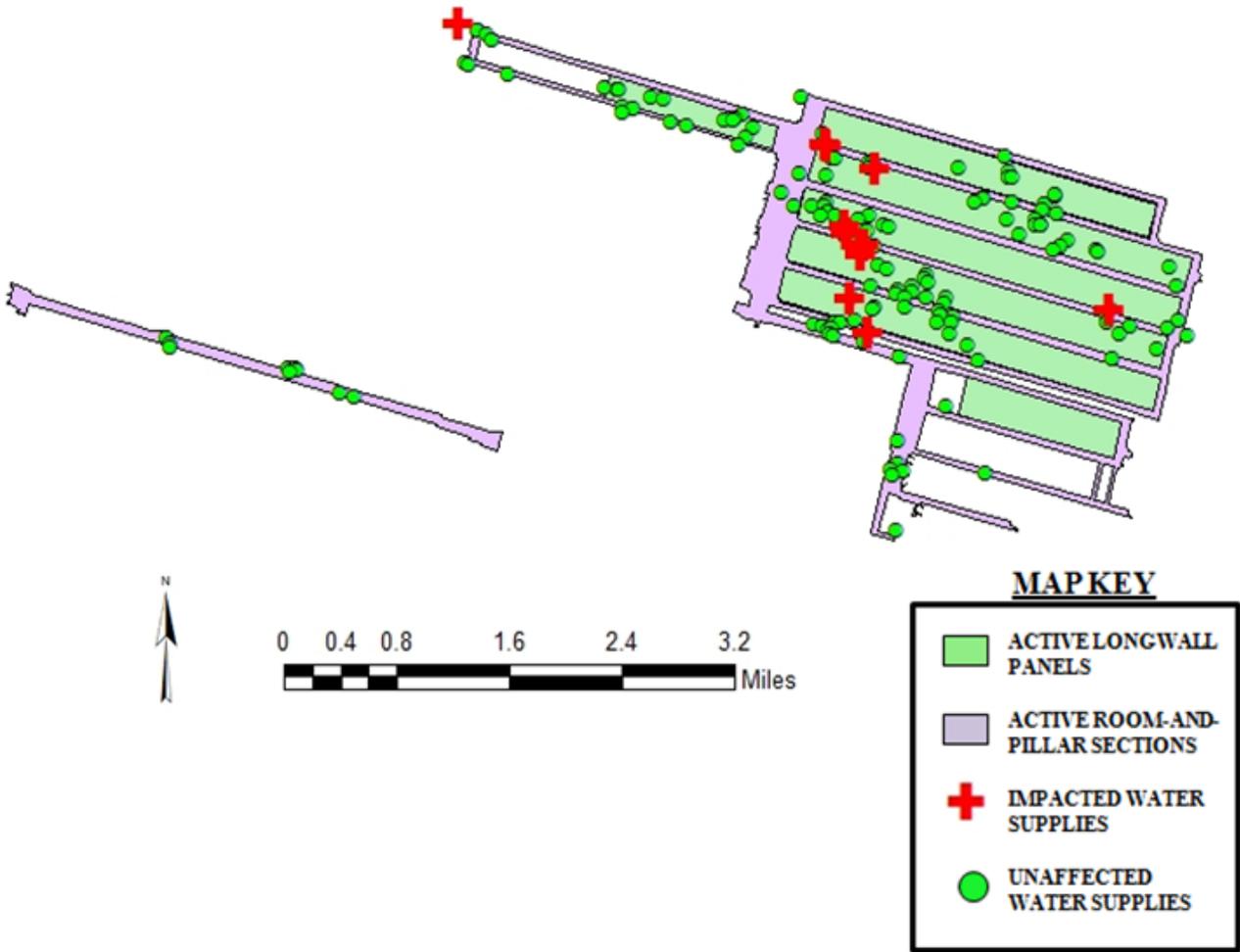
## MAPKEY

	ACTIVE LONGWALL PANELS
	ACTIVE ROOM-AND-PILLAR SECTIONS
	IMPACTED WATER SUPPLIES
	UNAFFECTED WATER SUPPLIES

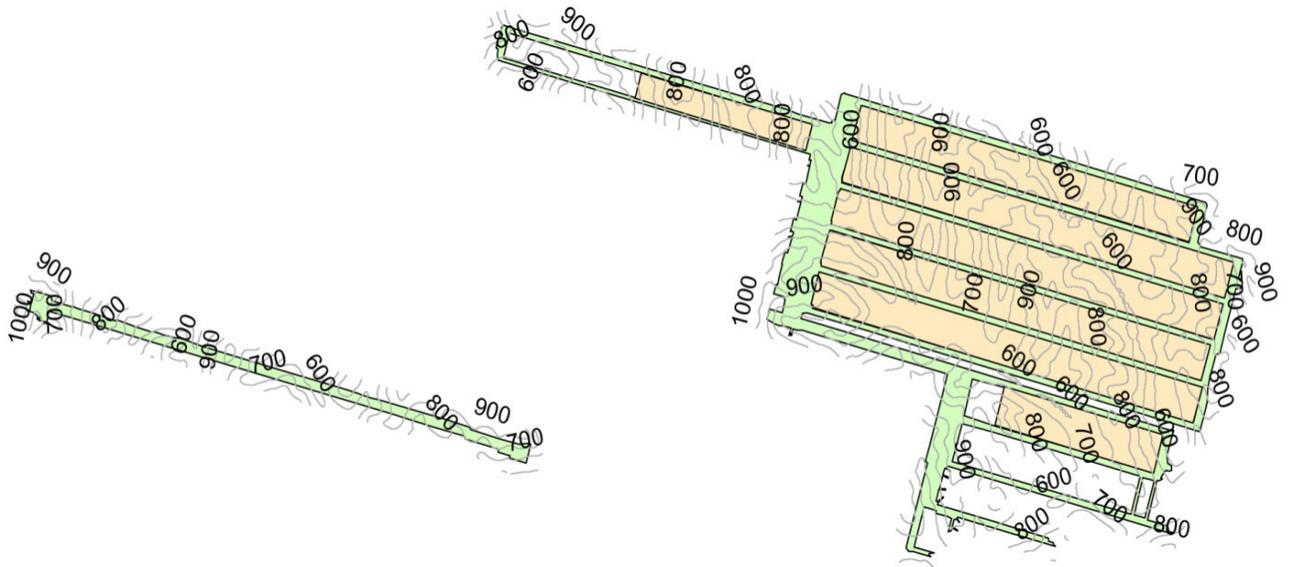
# BLACKSVILLE NO. 2 MINE OVERBURDEN



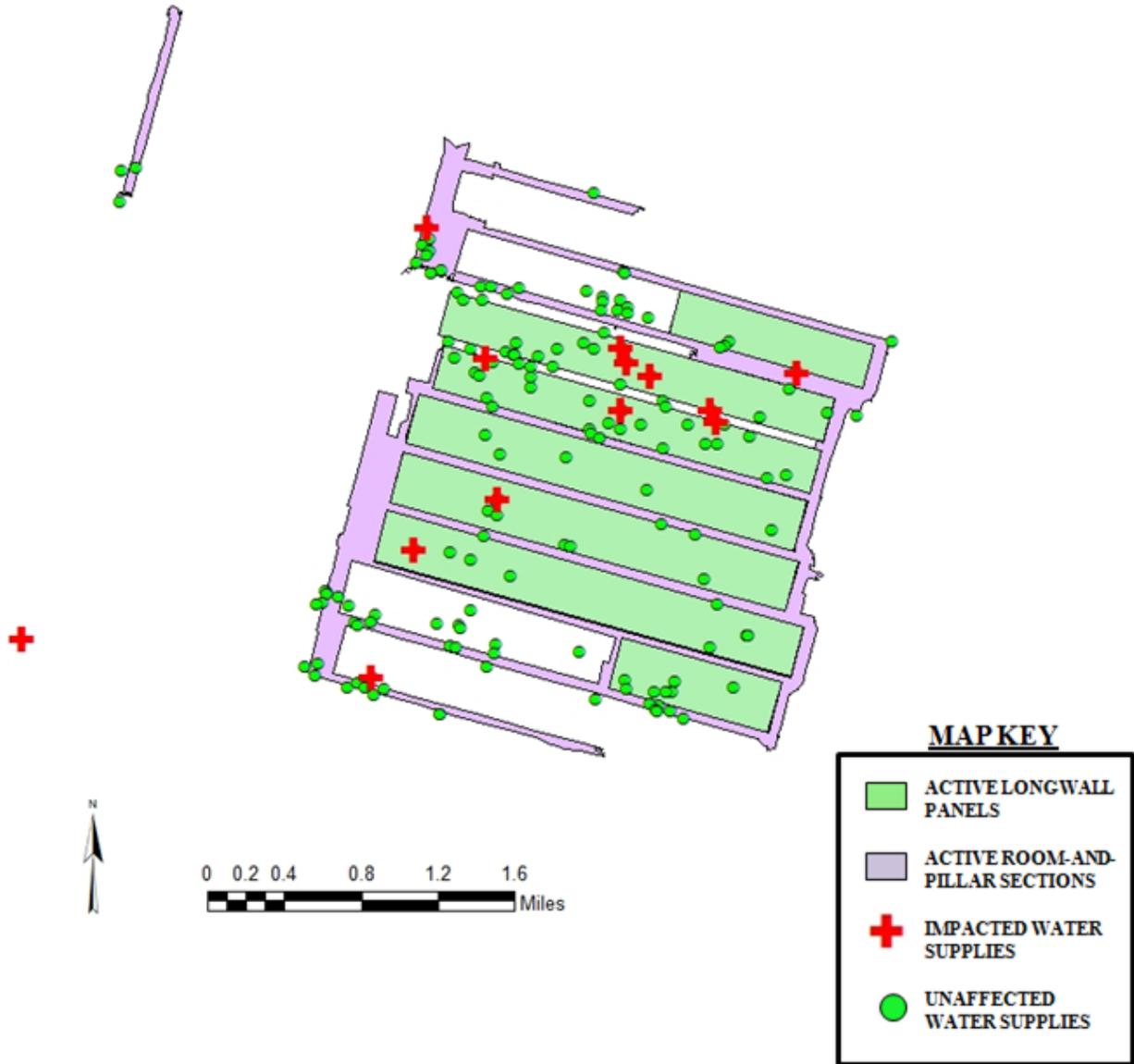
# CUMBERLAND MINE WATER SUPPLIES



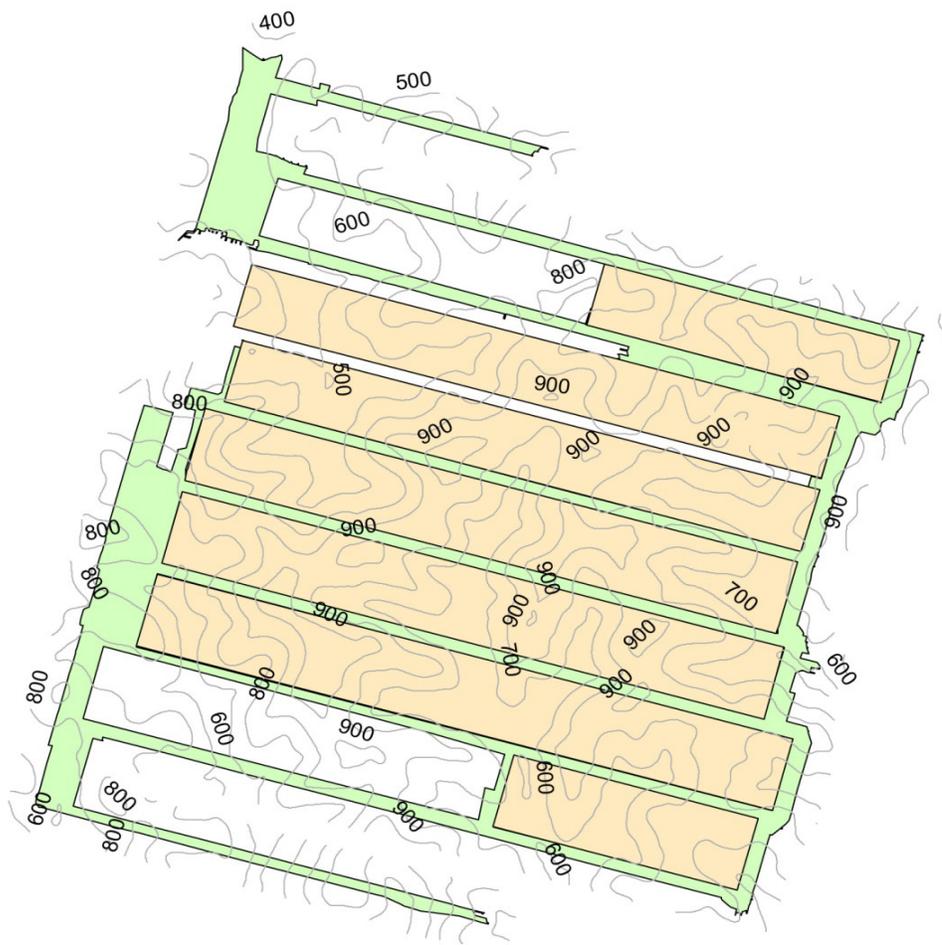
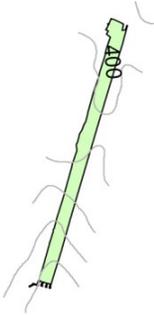
# CUMBERLAND MINE OVERBURDEN



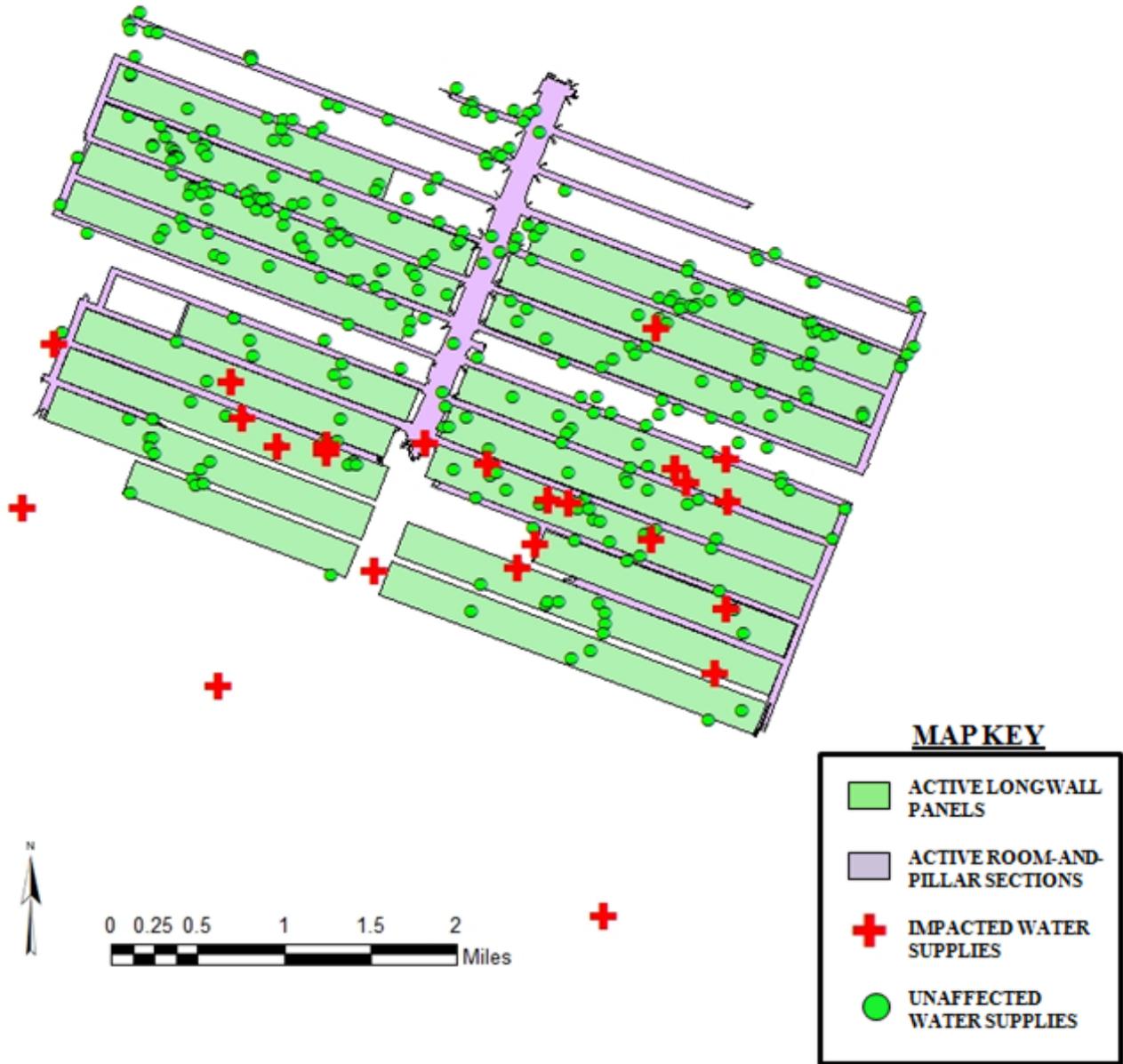
# EMERALD MINE WATER SUPPLIES



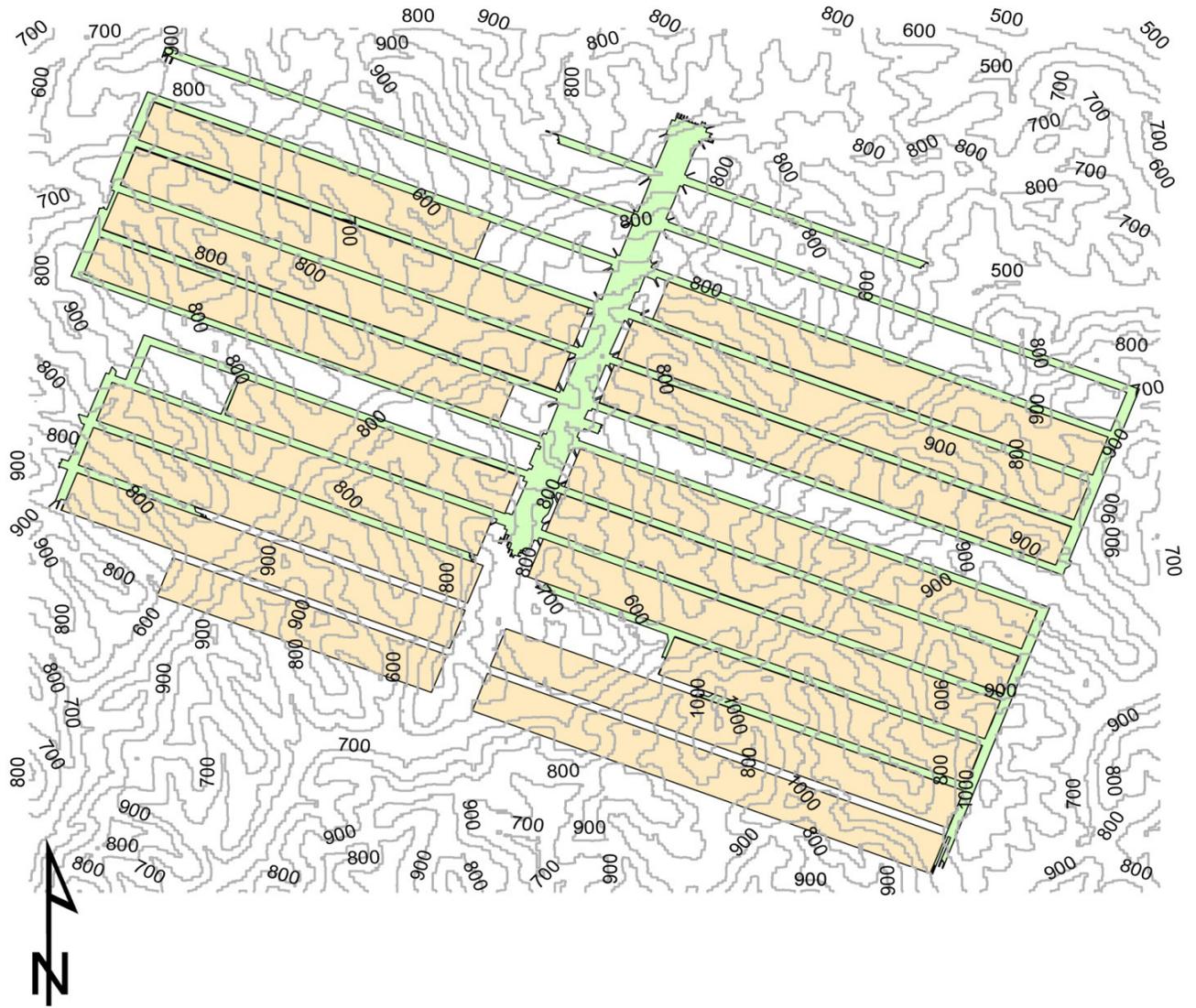
# EMERALD MINE OVERBURDEN



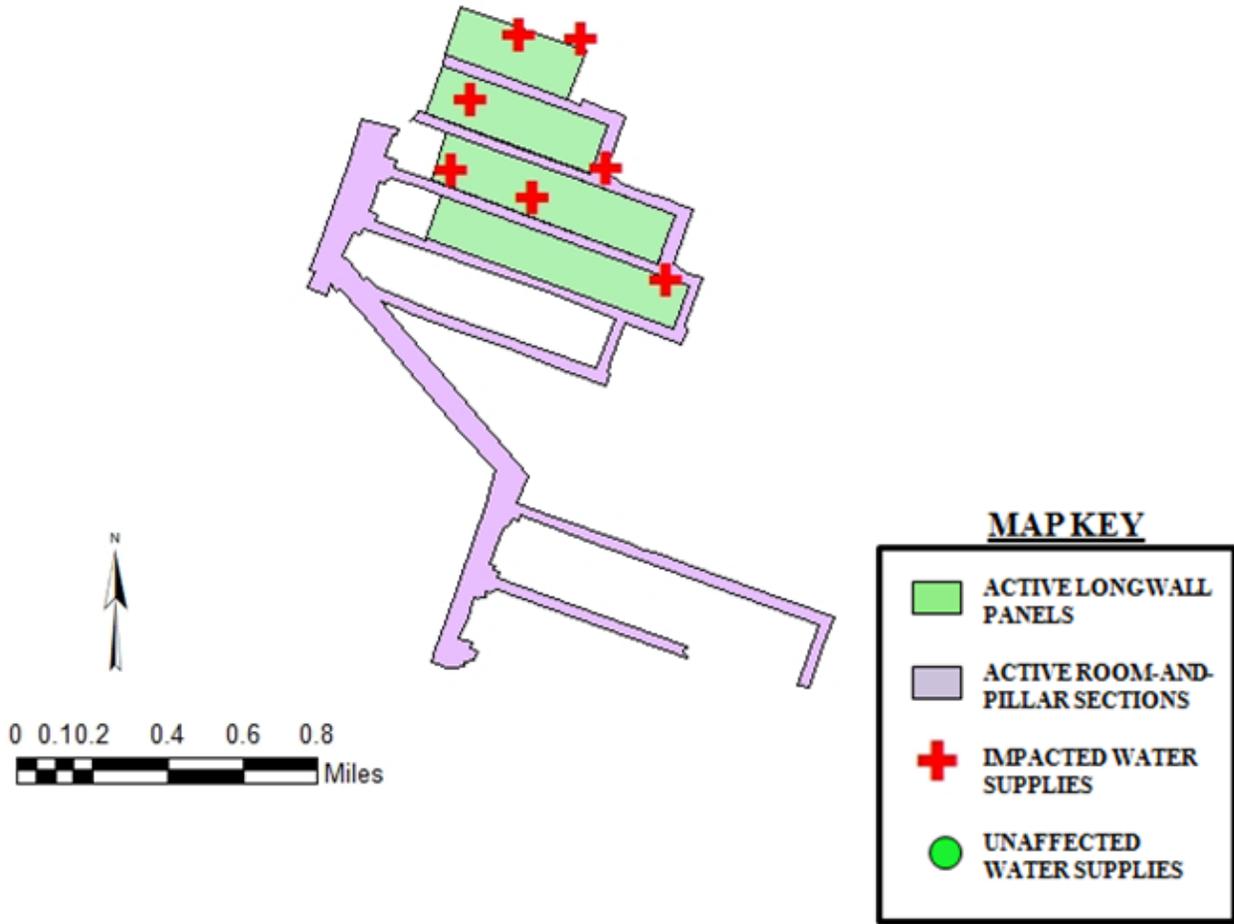
# ENLOW FORK MINE WATER SUPPLIES



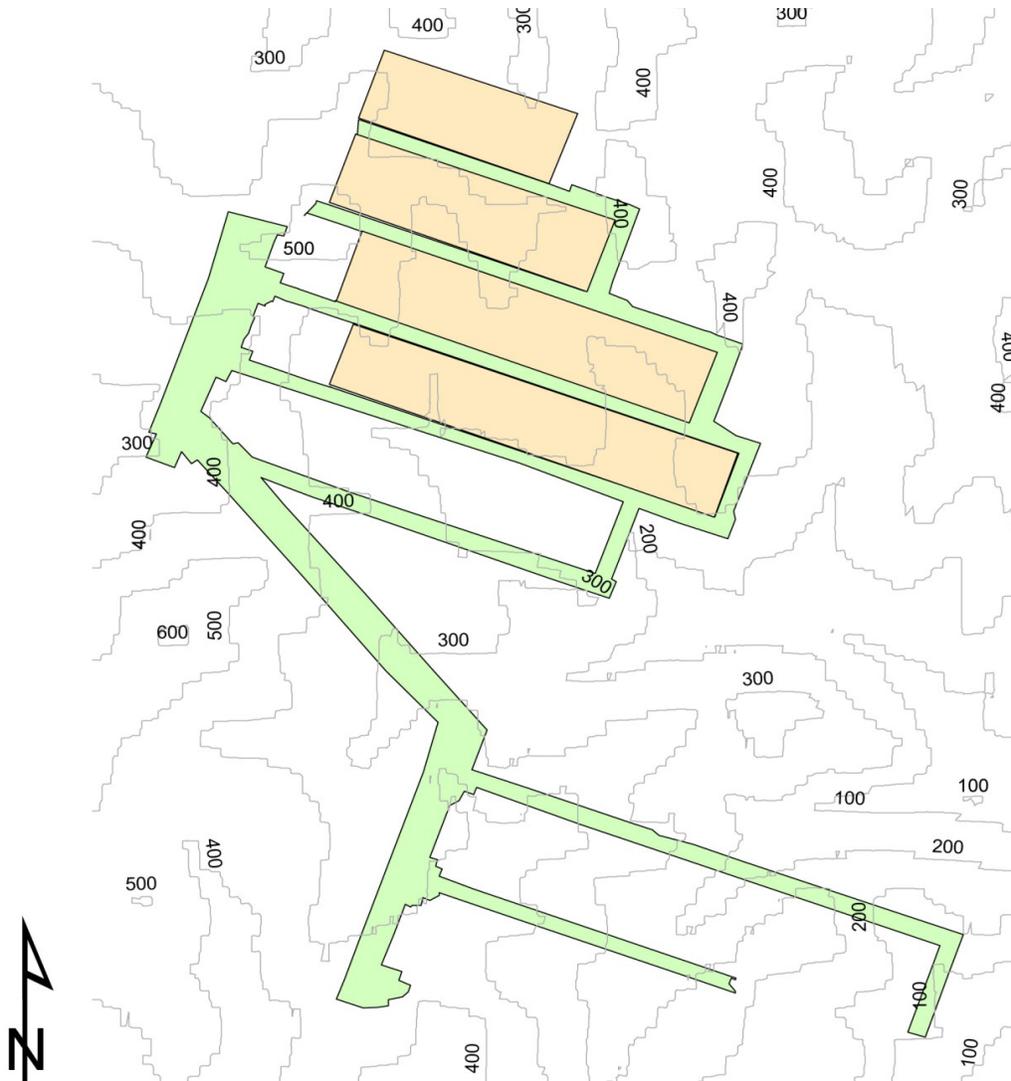
# ENLOW FORK MINE OVERBURDEN



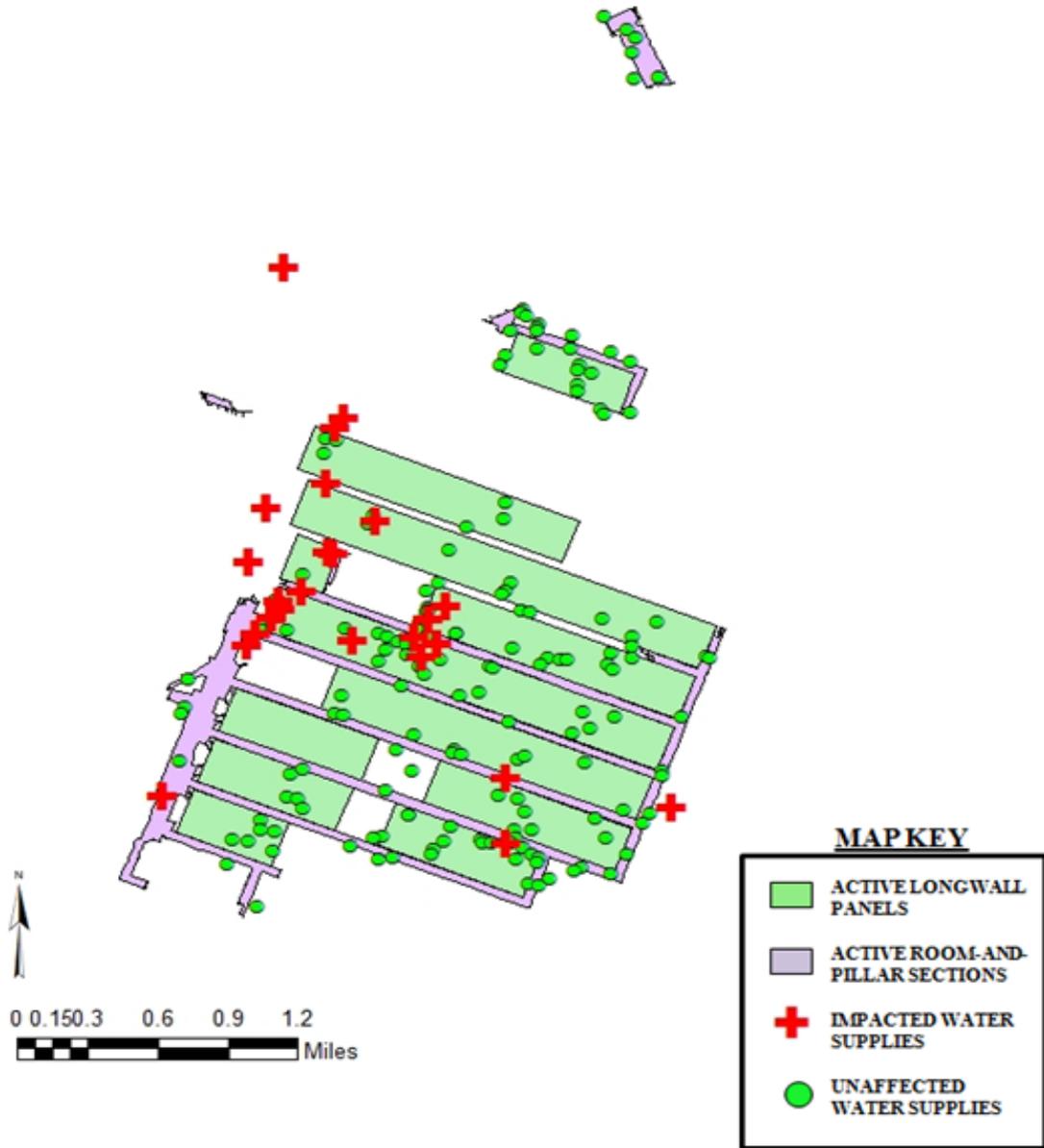
# HIGH QUALITY MINE WATER SUPPLIES



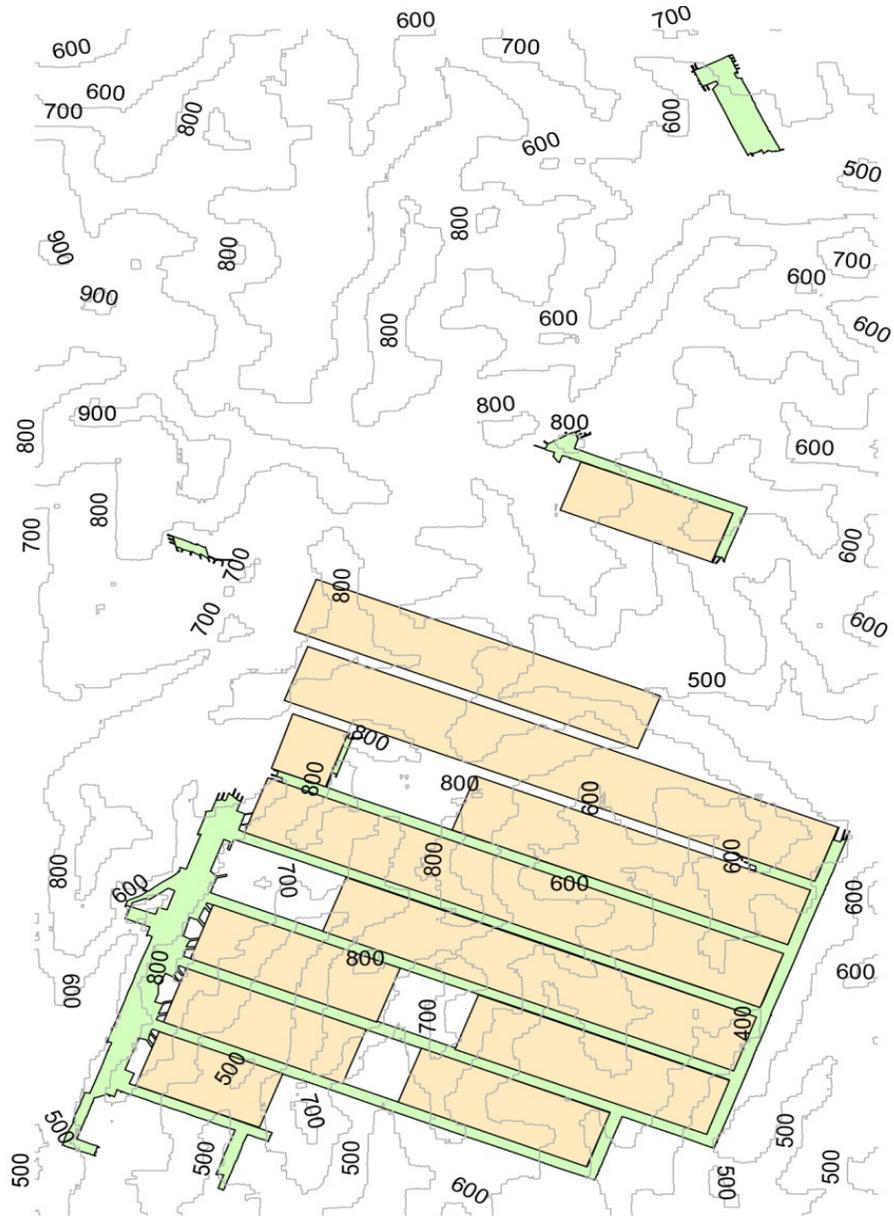
# HIGH QUALITY MINE OVERBURDEN



# MINE 84 WATER SUPPLIES



# MINE 84 OVERBURDEN



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