Preliminary Assessment of Factors Affecting Springs Undermined by Longwall Mines in Pennsylvania

Anthony Iannacchione
University of Pittsburgh, Pittsburgh, Pennsylvania

Daniel Bain
University of Pittsburgh, Pittsburgh, Pennsylvania

Michael Keener
University of Pittsburgh, Pittsburgh, Pennsylvania

Christopher Nealen
University of Pittsburgh, Pittsburgh, Pennsylvania

ABSTRACT

In Western Pennsylvania, springs provide a direct measure of the characteristics of perched groundwater aquifers. This paper examines how springs, classified as water sources by the Pennsylvania Department of Environmental Protection (PA DEP), are *affected* by coal mine subsidence. Our research aim is to determine important factors controlling spring performance, i.e., *affected* versus unaffected by longwall subsidence in Washington and Greene Counties, PA.

INTRODUCTION

Data analyzed in this report was collected by the PA DEP from the coal companies during the 3rd ACT 54 Assessment conducted by the University of Pittsburgh (Iannacchione, et al., 2011) in Pennsylvania. These data were contained within the permit files from seven Pennsylvania longwall coal mines operating from August 2003 to August 2008. The location of the areas mined by these seven longwall mines during the study period are shown in Figure 1a.

Of the more than 3,000 water sources, i.e., wells, springs, ponds, etc., identified in the 3rd ACT 54 Assessment, 1,400 are correlated with one of the seven longwall operations (Figure 1b). The database was refined to focus on springs undermined by longwall mining. Of 716 springs identified, 148 (21%) were *affected* by longwall mining. Figure 2 shows the distribution of *affected* springs (white dots) and unaffected springs (black dots). The term *affected* reflects a designation by the PA DEP and establishes company liability, i.e., diminution or contamination of the water source as a result of undermining, producing an action that

- repairs the water source,
- provides an equivalent water source, or
- compensates the land owner.

In Pennsylvania, a water supply can supply water for domestic drinking, farmland irrigation, livestock consumption or any other demonstrated use.

POTENTIAL FACTORS AFFECTING SPRINGS SUBJECTED TO LONGWALL SUBSIDENCE

This analysis focused on the relationships between the development of the subsidence basin and an *affect* to the springs designated as water sources by the PA DEP. The following factors are thought to impact the relationship between the formation of the subsidence basin and springs.

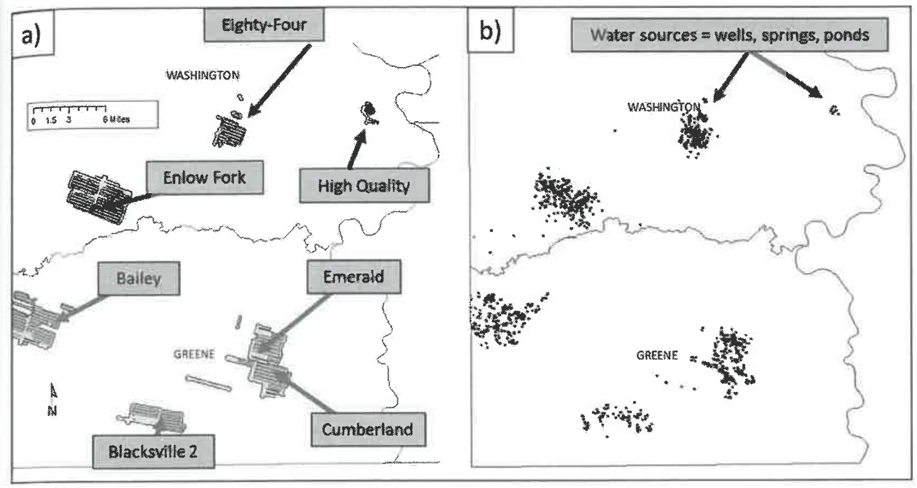

Figure 1. (a) Extent of mining that occurred from August 2003 to August 2008 at seven longwall mines in Washington and Greene Counties, Pennsylvania. The longwall panels are blue in color. Green represents the extent of all mining. (b) Location of the more than 1,400 water supplies (ponds, wells, and springs) undermined by longwall mining operations.

Factor 1, Geographic Location Within the Mining Environment

Surface deformations from longwall mining are capable of altering the character of fracture systems that feed springs in Greene and Washington Counties, PA. In some cases vertical deformations applied to bedding plane separations alter the behavior of fracture aquifer systems. The same can occur when horizontal deformations are applied to vertical joint systems.

To illustrate this, the Surface Deformation Prediction System or SPDS (Agioutantis and Karmis, 2012) was used to model the subsidence basin under a 1,500-ft wide panel at 800-ft of overburden. These are longwall panel dimension often used in current mining operations. Figure 3 demonstrates the vertical and horizontal deformation across the center of the modeled panel with a horizontal surface profile. A seven foot thick Pittsburgh Coalbed mine with 20-pct hardrock in the overlying strata will produce almost 3-ft of vertical subsidence in the center of the panel, reducing to zero over the adjacent gate entries.

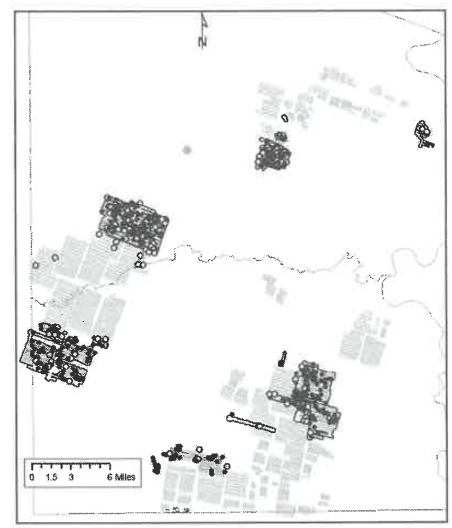

Figure 2. 716 springs located above or close to seven longwall mines operating between August 2003 and August 2008. Note the occurrence of *affected* springs (white dots) outside the mine's RPZ (thick black lines).

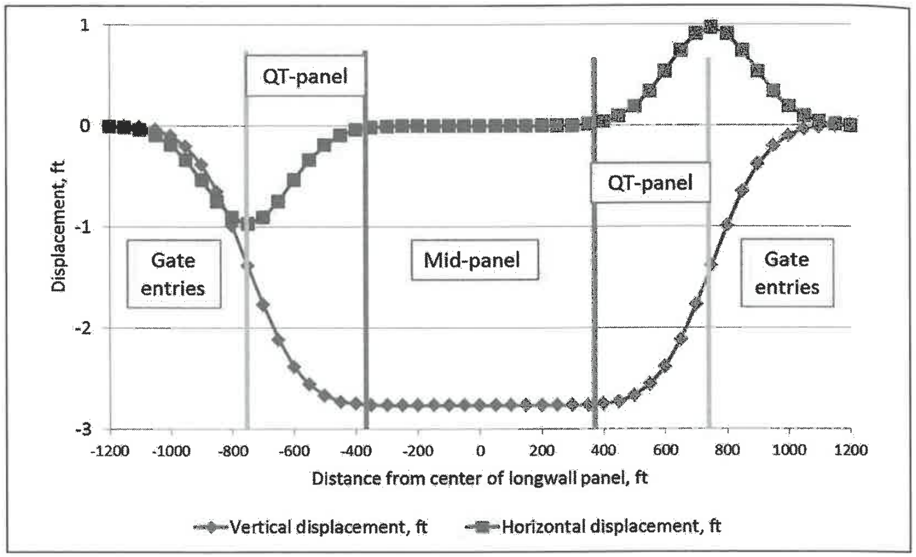

Figure 3. Relationship between vertical and horizontal deformations and the location within the subsidence basin

Table 1. Springs undermined and springs *affected* by longwall mining from August 2003 until August 2008 categorized by underlying mining environment

Mining Environment	Affected	Total	Percent of Total
Mid panel	43	188	23%
Quarter panel	32	187	17%
Gate road	29	127	23%
Outside of the mine	44	214	21%
Total	148	716	

Significant horizontal deformations are principally above the quarter-panel and gate entries typically moving into the center of the panel. The relationship between these deformation patterns and the occurrences of affected springs represents an area of future research.

Each spring was categorized by the underlying mining environment (Table 1). Four mining environments (Figure 4) were established: (1) *Mid Panel* or middle (inner) half of the longwall panel, (2) *Quarter Panel* or edge (outside) half of the longwall panel, (3) *Gate Road* including the longwall gate road entries as well as the adjacent room-and-pillar developments for the main and bleeder entries, and (4) *Outside the Mine* or within the region between the outside of the mine and the Rebuttable Presumption Zone (RPZ), Figure 4. The RPZ is a liability buffer created by projecting a 35-deg line from vertical, from the edge of mining to the surface (Anon, 1999). If the water supply falls within this 35-deg angle, the mining company is assumed liable for the impact, and it is their responsibility to dispute this assumption. All springs within the RPZ were analyzed. In addition, springs determined to be *affected* by mine subsidence outside the RPZ, albeit infrequent in occurrence, were also tracked and analyzed (Figure 5).

When analyzing the data from Table 1, we must realize that the category of Outside the Mine contained a wide variety of conditions, such as springs located over a longwall panel mined prior to August 2003. But what is most interesting about this data is that springs affected by longwall mining are not significantly influenced by the characteristics of the underlying mining environment, i.e., Quarter Panel, Mid

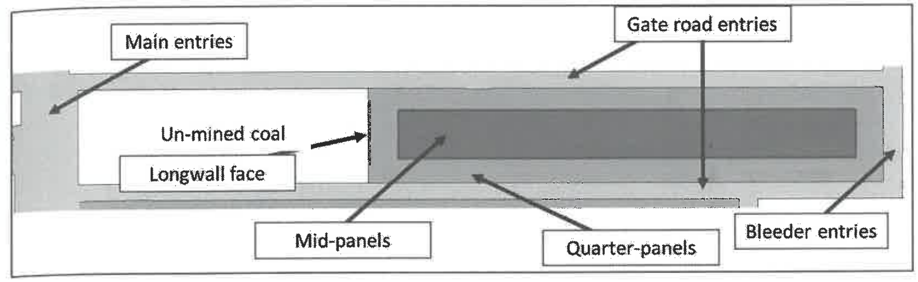

Figure 4. Mine layouts associated with mining environment categories used in Table 1

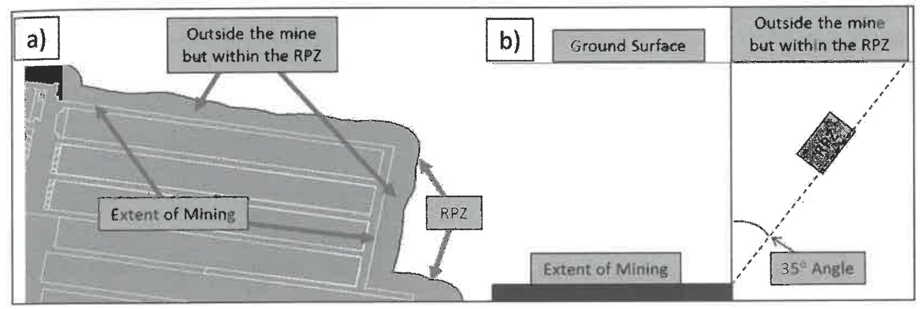

Figure 5. The category of "Outside the Mine" refers to the space between the outer limits of the mine and RPZ, (a) plan view, (b) cross-sectional view

Panel, Gate Road, or Outside the Mine. This is not what we would have suspected since springs located above the Quarter Panel and Gate Road are influenced by higher vertical and horizontal deformations then the Mid Panel (Figure 3), yet they are statistically equivalent to other underlying mining environments.

Factor 2, Topographic Position on the Surface

Each spring was categorized by the topographic position it occupied on the surface (Table 2). Three topographic positions were established: (1) Hilltop, (2) Hillside, and (3) Valley Bottom.

The topographic positions that are associated with the most *affected* springs are Hilltops and Valley Bottoms (Table 2). Hilltops are thought to contain the aquifers of the smallest areal extent while the opposite should be true for Valley Bottoms. Clearly more detailed analysis is needed.

Table 2. Topographic position of springs analyzed in this report

Topographic Position	Affected	Total	Percent of Total
Hilltop	22	73	30%
Hillside	76	456	17%
Valley bottom	50	187	27%
Total	148	716	

Factor 3, Geologic Characteristics of the Groundwater Aquifer

The dip of the formation and the characteristics of nature joints are important in determining where springs are located (Figure 6). In the vast majority of the data analyzed, springs occurred where the dip of the formation, within the hillside, causes the strata to rise in elevation away from the spring. The area comprised by these rising strata represent the maximum areal extent of

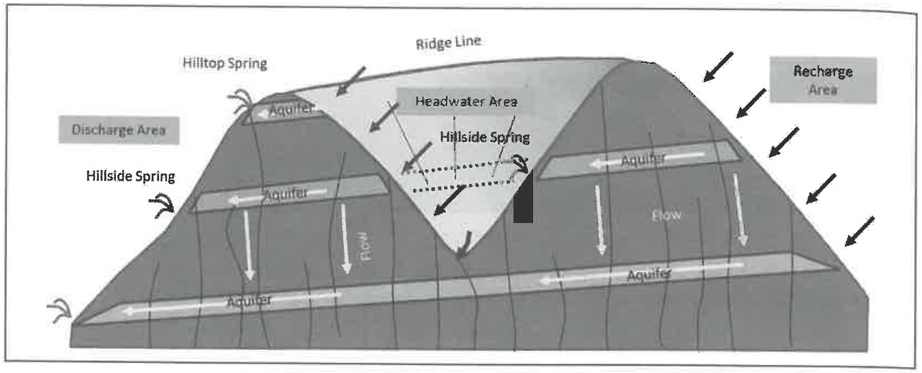

Figure 6. Generalized examples of how springs are influenced by formation dip and fracture orientations

the aquifer. Valley Bottoms should have the largest areal extent to their aquifers, Hilltops the least.

The 716 analyzed springs occurred within four geologic formations (Newport, 1973):

- *Quaternary Alluvium,* Quaternary System (0 to 63-ft thick)—Unconsolidated deposits overlying the bedrock in the major stream valleys. The material includes clay, silt, sand, gravel and some boulders and is generally permeable, and, where saturated, will yield moderate to large supplies of water.
- *Greene Formation,* Permian System (61 to 260-ft thick)—Comprised of the Fish Creek Sandstone and Donley Limestone Members. Sandstones grade irregularly into thin-bedded shaley sandstone and enclose several discontinuous thin shaley beds of limestone. A sandstone 10 to 40-ft thick is the most important water-yielding unit in this formation.
- *Washington and Waynesburg Formations,* Permian-Pennsylvania System (36 to 304-ft thick)—Comprised of alternating beds of shale, sandstone and coal. In general, poor water bearing formations.

Factor 4, Depth of Mining

The seven longwall mines varied in depth of mining from a minimum of 83-ft at the High Quality Mine to a maximum of 1,189-ft at the Blacksville No. 2 Mine (Table 3). The average longwall overburden was 687-ft with a standard deviation of 162-ft. Surface springs above shallow mining environments (High Quality) should produce more affects than deep mining environments (Blacksville No. 2). The authors believe the shallow longwall panels are within the fractured zone as defined by Peng (1992) while the deeper longwall panels are within the continuous deformation zone.

Table 3. Depth of mining characteristics for longwall mines

Mine	Avg.	SD*	Min.	Max.
Bailey	648	130	311	1061
Blacksville No. 2	887	106	649	1189
Cumberland	739	88	559	1029
Eighty-Four	627	109	362	885
Emerald	725	109	356	999
Enlow Fork	750	102	505	1036
High quality	338	71	83	544
Shoemaker	784	61	661	936
Total	687	162	83	1189

* SD = Standard Deviation

DETAILED WATERSHED EVALUATIONS

Short Creek Watershed

The Short Creek Watershed is located over the Enlow Fork Mine in Washington County, PA. Thirty-five springs were identified within the Enlow Fork Mine RPZ (Figure 7).

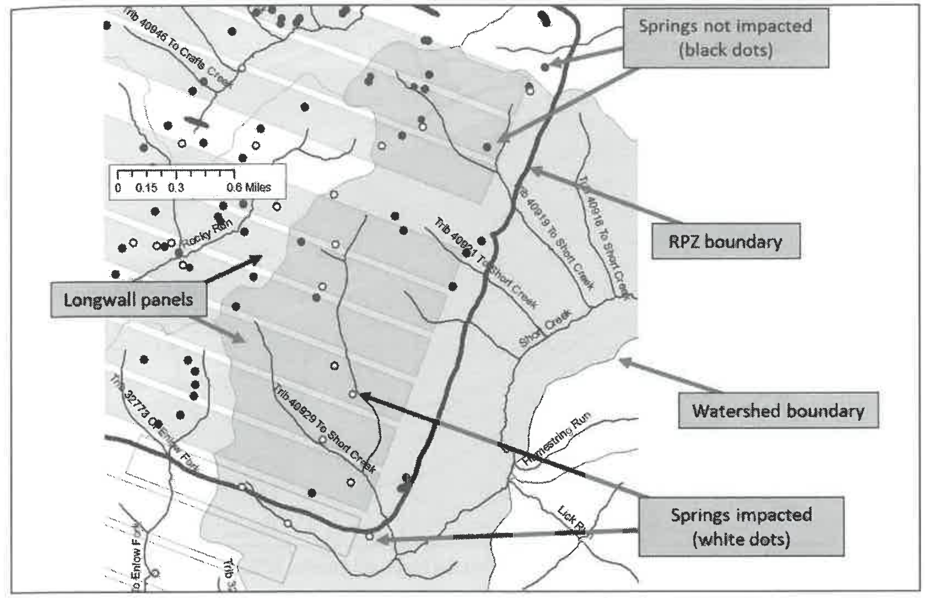

Figure 7. Short Creek Watershed showing the longwall panels, RPZ, and springs

Table 4. Distance of springs from the edge of the longwall panel or its position sorted mining environment within the Short Creek Watershed

Mining Environment	Affected	Total	Percent of Total
Mid panel	5	6	83%
Quarter panel	4	15	27%
Gate road	3	8	38%
Outside of the mine	1	6	17%
Total	13	35	

Geographic Location Within the Mining Environment

The location within the mining environments was determined for 35 springs. Thirteen springs were *affected* by longwall mining subsidence. The majority of the *affected* springs occurred over the Mid Panel and Gate Road mining environments (Table 4).

Topographic Position on the Surface

The topographic position of the springs undermined was analyzed. The majority of the springs were located within the hillside topographic position (74%) where 42% of these springs were *affected* (Table 5).

Table 5. Topographic position of springs within the Short Creek Watershed

Topographic Position	Affected	Total	Percent of Total
Hilltop	1	6	17%
Hillside	11	26	42%
Valley Bottom	1	3	33%
Total	13	35	

Geologic Characteristics of the Groundwater Aquifer

The majority of the springs are on the hillsides facing the down-dip structural trends of the strata. All springs within the Short Creek Watershed originated within the Greene Formation.

Depth of Mining

The average depth of mining for the 35 springs is 807-ft with a standard deviation of 69-ft.

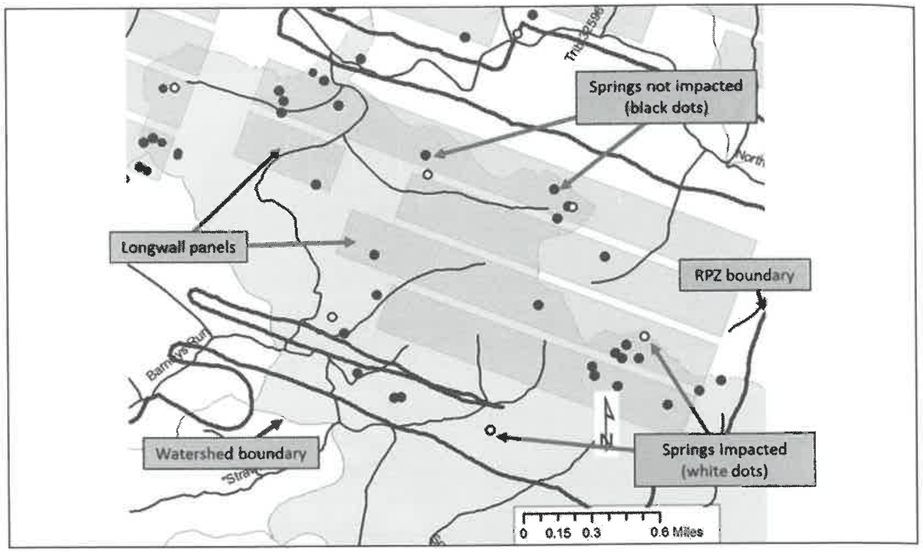

Figure 8. South Fork Dunkard Fork Watershed showing the longwall panels, RPZ, and springs

South Fork Dunkard Fork Watershed

The South Fork Dunkard Fork Watershed is located over the Bailey Mine in Greene County, PA. Forty springs were identified within the Bailey Mine RPZ (Figure 8).

Geographic Location Within the Mining Environment

The locations within the mining environment were determined for 40 springs. Thirteen springs were *affected* by longwall mining subsidence. The majority of the *affected* springs occurred over the Mid Panel and Gate Road mining environments (Table 6).

Topographic Position on the Surface

The topographic position of the springs undermined was analyzed. The percentage of springs *affected* are evenly distributed between the three topographic positions (Table 7).

Geologic Characteristics of the Groundwater Aquifer

While the majority of the springs are on the hillsides facing the down-dip structural trends of the strata several springs are located on the hillsides facing the up-dip structure trends. The water source for these springs are most likely natural joints and not perched aquifers.

Table 6. Distance of springs from the edge of the longwall panel or its position sorted mining environment within the South Fork Dunkard Fork Watershed

Mining Environment	Affected	Total	Percent of Total
Mid panel	2	14	14%
Quarter panel	1	11	9%
Gate road	3	11	27%
Outside of the mine	0	4	0%
Total	6	40	

Table 7. Topographic position of springs within the South Fork Dunkard Fork Watershed

Topographic Position	Affected	Total	Percent of Total
Hilltop	1	6	17%
Hillside	4	29	14%
Valley bottom	1	5	20%
Total	6	40	

Springs within the South Fork Dunkard Fork Watershed occur within the Greene, Washington, and Waynesburg Formations. Most of the springs occurred within the Greene Formation (27); however, only 4% of these were *affected* (Table 8).

Depth of Mining

The average depth of mining for the 40 springs is 691-ft with a standard deviation of 167-ft.

Maple Creek Watershed

The Maple Creek Watershed is located over the High Quality Mine in Washington County, PA. Six springs were identified within the High Quality Mine RPZ (Figure 9a).

Geographic Location Within the Mining Environment

The locations within the mining environment were determined for 6 springs. All six springs were *affected* by longwall mining subsidence. All mining environments within the study area have at least one *affected* spring (Table 9).

Table 8. Geologic formation associated with springs within the South Fork Dunkard Fork Watershed

Formation	Affected	Total	Percent of Total
Greene	4	27	4%
Washington	1	6	17%
Waynesburg	1	7	14%
Total	6	40	

Topographic Position on the Surface

The topographic position of the springs undermined was analyzed. Eighty percent of the springs *affected* are within the Hilltop area (Table 10).

Geologic Characteristics of the Groundwater Aquifer

Springs within the Maple Creek Watershed occur in the Waynesburg Formation. Closer examination of local geology, while somewhat limited by available data, suggests that lithology of the water bearing zones may influence spring impacts during or following subsidence (Figure 9b). The test hole data collected for generating this section are

Table 9. Distance of springs from the edge of the longwall panel or its position sorted mining environment within the Maple Creek Watershed

Mining Environment	Affected	Total	Percent of Total
Mid panel	4	4	100%
Quarter panel	1	1	100%
Gate road	1	1	100%
Outside of the mine	0	0	0%
Total	6	6	

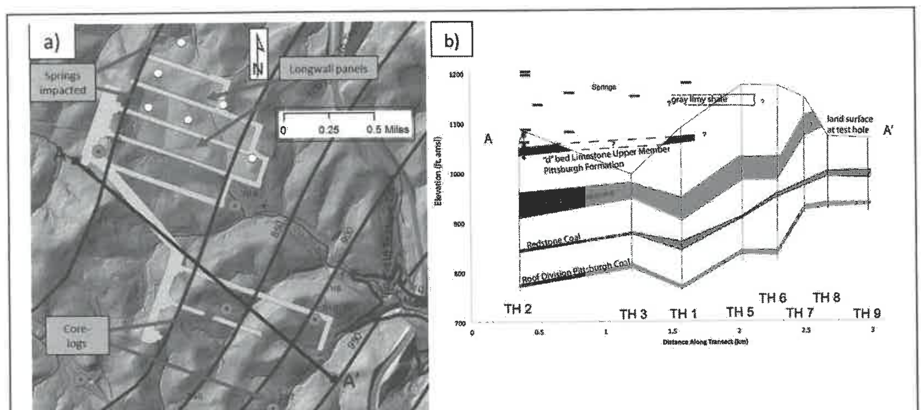

Figure 9. (a) longwall panels, springs affected, core-logs, and structure contour on the Pittsburgh Coalbed at the High Quality mine; (b) stratigraphy in various test holes at location along the transect A-A'

located predominantly in southern, topographically lower portions of the study area. However, historically impacted streams are located mainly in northern, topographically higher portions. Despite this spatial divide, we expect the stratigraphy to be reasonably consistent across both groups of data. Available data suggests the water bearing zone in a water well located near the transect sits just above the 'd' bed of the Limestone Upper Member of the Pittsburgh Formation (grey diamonds in Figure 9b) . In addition, the available data from the higher elevations indicates a relatively thick ~20-ft layer of "gray limy shale" at elevations similar to several of the affected springs. All of the springs seemingly arising from this gray limy shale were affected following long wall mining, suggesting this rock material may be

Table 10. Topographic position of springs within the Maple Creek Watershed

Topographic Position	Affected	Total	Percent of Total
Hilltop	5	5	100%
Hillside	1	1	100%
Valley bottom	0	0	0%
Total	6	6	

particularly prone to deformation causing substantial changes in hydrologic flowpaths.

Depth of Mining

The average depth of mining for the 6 *affected* springs is 385-ft with a standard deviation of 49-ft.

Dyers Fork Watershed

The Dyers Fork Watershed is located over the Cumberland Mine in Greene County, PA. Forty-two springs are identified within the Cumberland Mine RPZ (Figure 10).

Geographic Location Within the Mining Environment

The locations within the mining environment were determined for 42 springs. Eight springs were *affected* by longwall mining subsidence. The mining environment locations are evenly distributed (Table 11) with the exception of Gate Roads.

Topographic Position on the Surface

The topographic position of the springs undermined was analyzed. The largest number of springs are located on hillsides (Table 12).

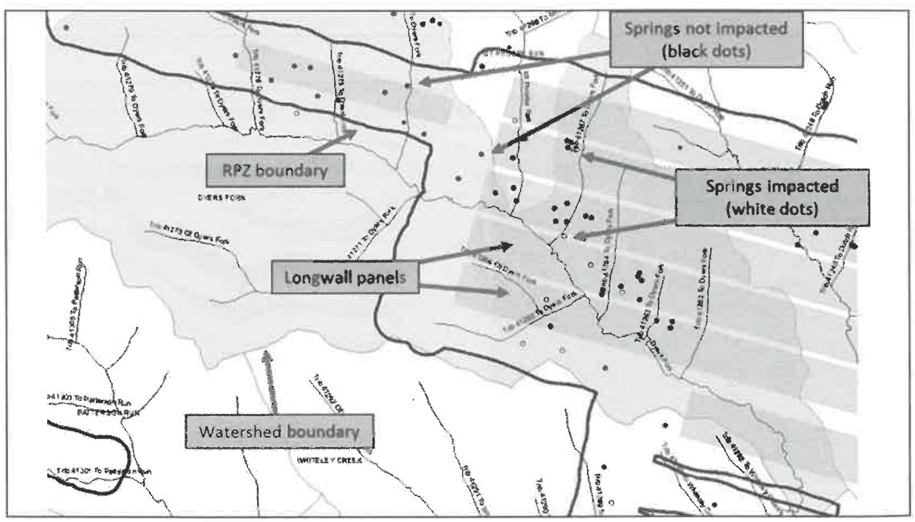

Figure 10. Dyers Fork Watershed showing the longwall panels, RPZ, and springs

Table 11. Distance of springs from the edge of the longwall panel or its position sorted mining environment within the Dyers Fork Watershed

Mining Environment	Affected	Total	Percent of Total
Mid panel	2	14	14%
Quarter panel	2	12	17%
Gate road	3	10	30%
Outside of the mine	1	6	17%
Total	8	42	

Table 12. Topographic position of springs within the Dyers Fork Watershed

Topographic Position	Affected	Total	Percent of Total
Hilltop	1	3	33%
Hillside	3	25	12%
Valley bottom	4	14	29%
Total	8	42	

Table 13. Geologic formation associated with springs within the Dyers Fork Watershed

Formation	Affected	Total	Percent of Total
Greene	2	11	18%
Washington	6	31	14%
Total	8	42	

Geologic Characteristics of the Groundwater Aquifer

While the majority of the springs are on the hillsides facing the down-dip structural trends of the strata several springs are located on the hillsides facing the up-dip structure trends. The water source for these springs are most likely natural joints and not perched aquifers. Springs within the Dyers Fork Watershed occur within the Greene and Washington Formations. Most of the springs occurred within the Greene Formation (27); however, only 4% of these were *affected* (Table 13).

Depth of Mining

The average depth of mining for the 42 springs is 701-ft with a standard deviation of 74-ft.

SUMMARY

Over 1,400 water sources from 7 longwall mining operations were analyzed. Of this total, 716 are springs. 148, or 21%, of these springs were designated as *affected* by longwall subsidence.

Four factors were examined: (1) geographic location within the mining environment, (2) topographic position on the surface, (3) geologic characteristics of the groundwater aquifer, and (4) depth of mining. In addition, four mining environment, i.e., Mid Panel, Quarter Panel, Gate Roads, and Outside the Mine, and three topographic, i.e., Hilltop, Hillside, and Valley Bottoms, categories were established and analyzed.

- When examining the entire database, all mining environments *affected* springs.
- Most springs are located along hillsides (64%).
- The dip of the formation was found to be consistently important in determining the occurrences of springs. Some variations were observed but could not be explained by this analysis.
- The depth of mining was measured for each spring. On average, mining occurred approximately 690-ft below the springs.
- No discernible trends were found when analyzing formation types versus spring frequency or *affects*.

Important Facts

- Springs *affected* by longwall mining are not significantly influenced by the characteristics of the underlying mining environment, i.e., Quarter Panel, Mid Panel, Gate Road, or Outside the Mine.
- The topographic position most associated with *affected* springs are hilltops and valley bottoms (49% of *affected* springs but only 36% of total springs).
- More detailed analysis is needed to understand how a small number of springs are forming up-dip of the strata. It is recommended that additional analysis be completed that would use joint surveys and

Landsat imagery to investigate the role of fracture permeability.

- Details of the geologic members associated with springs are not available and prohibits an appropriate evaluation of this factor.
- The Short Creek Watershed (35 springs) has a relatively moderate number of *affected* springs (37%), a high percentage of Mid Panel *affected* springs (5 of 6), and a spring to mining depth that average 807-ft. All springs are located within the Greene Formation.
- The South Fork Dunkard Fork Watershed (40 springs) has a relatively low number of *affected* springs (15%), a low percentage of Quarter Panel *affected* springs (1 of 11), and a spring to mining depth that averages 691-ft. Springs occurred in all three formations with the most in the Greene Formation.
- The Maple Creek Watershed (6 springs) had 100% of its springs *affected*. The most likely reason for this is the low spring to mining depth (average 385-ft). All of the springs occurred in the Waynesburg Formation. However, this preliminary analysis indicates a more complete understanding of geologic context, when combined with subsidence modeling, may provide important insight into the hydrologic impacts of subsidence resulting from long wall mining.
- Dyers Fork Watershed (42 springs) has a relatively low number of *affected* springs (19%), a moderate percentage of Gate Road *affected* springs (3 of 10), and a spring to mining depth that averages 701-ft. All of the springs occurred in the Greene Formation.

Of the four factors examined, depth of mining below the springs had the most obvious affect. Mining environment and topographic position had only moderate *affects* on the watershed scale and no obvious *affects* on a regional scale. More detailed information on local fracture patterns and geologic conditions associated with springs are needed to fully analyze the characteristics of the groundwater aquifer.

ACKOWLEDGMENT

This study was sponsored by the Appalachian Research Initiative for Environmental Science (ARIES). The views, opinions and recommendations expressed herein are solely those of the authors and do not imply any endorsement by ARIES employees, other ARIES-affiliated researchers or industrial members. Information about ARIES can be found at http://www.energy.vt.edu/ARIES.

REFERENCES

Agioutantis, Z. and Karmis, M. 2012. "Surface Deformation Prediction System for Windows version 6.1, Quick Reference Guide and Working Examples," Virginia Polytechnic Institute and State University, August 17, 2012, 273 p.

Anon. 1999. "Water Supply Replacement and Compliance," PA DEP, Bureau of Mining and Reclamation, Document Number 562-4000-101, 43 p.

Iannacchione, A., Tonsor, S.J., Witkowski, M., Benner, J., Hale, A. and Shendge, M. 2011. "The Effects of Subsidence Resulting from Underground Bituminous Coal Mining on Surface Structures and Features and on Water Resources, 2003 to 2008," PA DEP Website http://www.dep.state.pa.us/dep/deputate/minres/bmr/act54_2008_report/cover.htm, published January 10, 2011, 499 pages and 1 plate.

Newport, T.G. 1973. "Ground-Water Resources of Washington County, Pennsylvania," Water Resource Report 38, Pennsylvania Geologic Survey, 31 p.

Peng, S.S. 1992. *Surface Subsidence Engineering*, Society of Mining, Exploration, and Metallurgy, 161 p.