FACTORS INFLUENCING THE EFFECTS OF UNDERGROUND BITUMINOUS COAL MINING ON WATER RESOURCES IN WESTERN PENNSYLVANIA

by

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Coal mining in Pennsylvania has been fundamental to the commonwealth's economy for over 150 years. Since that time, over 1.2 million acres of bituminous coal have been mined using underground mining methods. Pennsylvania is also estimated to have over one million domestic water wells over its 29 million acres area. From 2003 to 2008, 2,789 water supplies were undermined with about 24.5% having reported impacts. However, not all reported impacts are related to mining. The effects of underground coal mining on the utility of these wells and other water resources have only been studied systematically within the past 20 years and are still not completely understood.

Pennsylvania amended its Bituminous Mine Subsidence and Land Conservation Act (Act 54) in 1994. The amended act requires that a report be submitted every five years that assesses the impacts on water resources and structures due to underground coal mining. Well and spring effects can be classified into two categories: water loss (diminution or total loss of water) and water contamination (reduced quality, increased metals, gas, etc.). Once these types of effects are identified, they are analyzed to determine the relationship between underground coal mining and water resource quality and quantity.

This study investigates the factors associated with water loss and water contamination due to underground coal mining. The study area includes all underground bituminous coal mining activity in Pennsylvania from August 21, 2008 to August 20, 2013. The area encompasses 10 counties in western Pennsylvania providing a diverse sample of water resource data, mining methods, and local conditions. Mining activity was conducted by 6 companies with a total of 7 longwall mines and 39 room-and-pillar mines. Factors include mining method, mining depth, proximity to mining, hydrogeological setting, topographical setting, climate, and more. A statistical analysis of these factors is used to determine the most important factors driving water resource impacts. Greater study is then conducted on the most significant factors using geographic information systems (GIS) and modeling software to better understand how effects are caused and how they can be mitigated or eliminated.

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1.0 INTRODUCTION

Coal mining has been associated with Pennsylvania's economy for over 150 years. From the small anthracite mines in northeast to the massive bituminous longwall mines in the southwest, Pennsylvania has some of the most diverse coal reserves in the country. The anthracite region provides heating coal with high calorific content and low impurities. Much of the bituminous coal is used as steam coal for electric generation to power homes and industries across the state. The remainder of bituminous coal is classified as metallurgical coal and is used in the production of steel as coke. In 2011 Pennsylvania was ranked fourth in coal production in the United States behind Wyoming, West Virginia, and Kentucky. The state produced over 59 million short tons (EIA 2011). Also in 2011 Pennsylvania consumed 54.8 million short tons of coal, making it a net exporter of coal (EIA 2011b). Coal mining has the potential to support Pennsylvania's economy for decades to come.

From 2003 to 2008, 2,789 water supplies were undermined with about 24.5% having reported impacts, although not all impacts are linked to mining. Public and private water wells can be impacted due to changes caused by mining in groundwater aquifers. Over a million wells are estimated within Pennsylvania (DCNR 2013). Other water supplies, such as springs used for domestic or agricultural purposes, can also be affected by underground mining. Springs not used for domestic or agricultural purposes are difficult to quantify since not all are located. Additional information is needed to help minimize affects to these water supplies.

This thesis will investigate new data gathered from 2008 to 2013 by the PA DEP for the 4^{th} Act 54 report and utilize the most current techniques to help improve prevention controls and recovery measures. The following sections include a comprehensive literature review to examine models and theories related to mine subsidence and groundwater, a discussion of the procedure used for analysis, including data and case studies, and interpretation of the results. The conclusions will summarize the factors that are most influential to water supplies due to underground coal mining. The conclusions will also state when these factors become significant. Finally, recommendations will be made to remedy difficulties faced during this analysis for future studies.

2.0 LITERATURE REVIEW

A literature review was conducted to understand hydrogeological and mine subsidence theory. These theories aid in the analysis of water supply issues related to mining activities. The review also facilitated determination of variables associated with water supply issues in undermined areas. These variables are used to further assess the relationship between underground mining and the hydrogeological system.

2.1 HYDROGEOLOGICAL THEORY

Hydrogeology is the study of groundwater flow in the aquifer system. The two major types of aquifers are unconfined and confined. Unconfined aquifers are located close to the land surface and extend in thickness down to a confining layer. A confining layer is a relatively low permeable unit that has the capability of transmitting water slowly. Since the unconfined aquifer is located near the surface, much of the material in the aquifer consists of soil, alluvium, glacial drifts, and broken and fractured rock. Recharge into unconfined aquifers occurs by infiltration of surface waters (precipitation, surface runoff, streams, rivers, lakes, reservoirs, ponds, etc.) through the unsaturated zone. Recharge can also occur from underlying aquifers seeping through a confining layer. Discharge occurs when the potentiometric surface intercepts the ground surface, when a well extracts water from the aquifer, or when seepage occurs through a confining layer. Confined aquifers are located between confining layers. Confined aquifers have the potential to become pressurized. Porous rocks such as limestone and sandstone are the materials that generally compose a confined aquifer. The porosity allows water to flow easily through the rock. Recharge is accomplished by infiltration of surface water to an outcrop of the aquifer or by seepage through neighboring aquifers. Surface discharge occurs through extraction wells and seepage (Fetter 2001).

Hydrogeological theory generally assumes that both types of aquifers occur in homogeneous material. This assumption allows for the use of Darcy's Equation:

$$q = K\frac{dh}{dl} \tag{2-1}$$

where,

- q = linear flow rate, ft/s

- K = hydraulic conductivity, ft/s
- $\frac{dh}{dl}$ = hydraulic gradient; change in head over change in flow length

This simple one-dimensional form of Darcy's Law can be used to calculate velocity of a fluid through a homogeneous media at steady state. The most important concept of Darcy's Law to be remembered is that fluid flows from areas of high head to areas of low head (Callaghan, et. al 2001). Steady state allows for the changes in velocity of the fluid to be neglected through the media. Homogeneity is important because the hydraulic conductivity is assumed to be constant throughout the length of the material. Therefore, the scale at which a material is measured must be large enough for small discontinuities to be neglected. Consistent porosity is known as primary porosity. Non-consistent porosity is known as secondary porosity and consists of fractures, faults, discontinuities, and non-homogeneity. Groundwater flows more freely through areas of secondary porosity due to relatively larger pore spaces and long, continuous openings. This entails that groundwater flows primarily through areas of secondary porosity (Wyrick and Borchers 1981).

Secondary porosity can be formed by natural or man-made events. Natural events include stress-relief fracturing and tectonic movements. Stress-relief fracturing occurs when a valley has been created by the erosion of the rock structure. The eroded material no longer provides a confining pressure to the rock. This change in pressure induces expansion of the rock causing fractures to occur in areas of weakness. Most fractures occur in zones where the rock is experiencing tensile forces. Bedding plane separations can also occur allowing for increased porosity. Compressional fractures occur if the force compressing the rock exceeds the compressive strength of the rock. These fractures and separations provide conduits for groundwater to flow and can connect different aquifers to each other and the ground surface (Booth 2002).

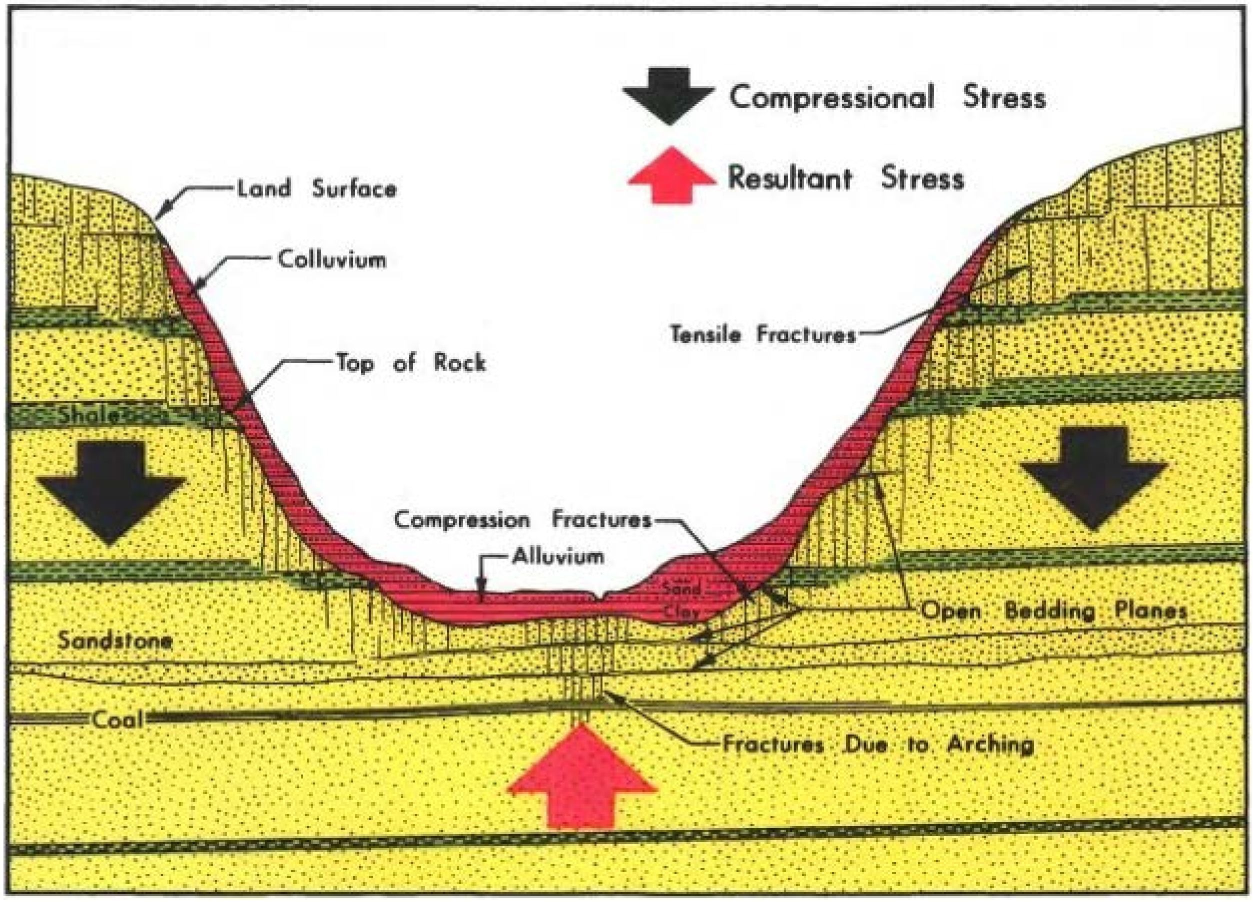


Figure 2.1: Generalized geologic section showing features of stress-relief fracturing (Ferguson 1974)

Tectonic movements can also greatly increase secondary porosity, but tectonic movements vary in magnitude so determining an understanding of how secondary porosity occurs is limited. Fractures can occur between faults or during bending of the rock structure.

Man-made events include large excavation projects and underground mining. Large excavation projects are similar to stress-relief fracturing. Large amounts of earth is removed no longer providing a confining pressure. The rock is allowed to move and fracture. Vertical fractures form that can extend through different rock layers and bedding planes separate.

Underground mining events have similar effects with tectonic movements, but the effects of subsidence are better characterized and, therefore, more predictable. Studies, such as Kendorski, and data have shown that aquifers generally experience a drop in head when undermining occurs. Outcomes after the drop in head include full recovery of the water table after mining due to closing of the secondary pores and fractures after mining. The areas of secondary porosity may return to a pre-mining state once the rock has reached an equilibrium. A permanent drop in the water table due to increased transmissitvity through the aquifer and between aquifers can also occur. This is also related to increases in secondary porosity. Greater well yields and/or poor quality water can also occur. Mechanisms inducing secondary porosity during underground mining are discussed in the next section.

2.2 SUBSIDENCE THEORY

Subsidence theory is mostly applied to longwall mining but also applied to other full extraction mining methods. During longwall mining an opening is created within the earth. The overlying material collapses into this opening. The movement of the collapsing material propagates to the surface. The properties that influence longwall subsidence include thickness of the overburden rock, physical properties of the overburden rock, geometry and orientation of the longwall panel, extraction thickness, and surface topography (PA DEP 1999).

Longwall subsidence can be divided into four major zones: caving zone, fractured zone, continuous deformation zone, and soil zone (Peng 2008). Each zone is classified based on unique properties. It is important to note that these zones and properties are classified based on data in the Northern Appalachian region.

The caving zone is immediately above the extracted coal seam. The rock fills the mine void in an irregular schism. The rock loses its continuity and bedding and becomes a pile of rubble in the mine void. The thickness of this zone has been found to be 2 – 8 times the extraction height or coal seam thickness.

The fractured zone is located immediately above the caving zone. The rock in this zone maintains its bedding structure but is greatly fractured and deformed. Fracture density is higher at the bottom of the zone and decreases moving towards the top of the zone. The amount of fracturing and deformation greatly increases the porosity of the rock in this zone. Vertical fractures can extend through different rock layers, allowing potential hydraulic connections between aquifers. The thickness of the fractured zone is 30 – 50 times the extraction height.

The continuous deformation zone is located immediately above the fractured zone. Strata in this zone maintains its continuity and is allowed to deform by bending. Small fractures can occur but generally do not extend through rock layers. Bedding separations between layers can also occur. Separations and fractures lead to increased porosity of the rock in this zone. The thickness of this zone extends from the fractured zone to the soil zone.

The final zone is the soil zone. This zone is located directly above the continuous deformation zone. This zone is classified because the composition of the material in this zone consists of soil and broken rock. Fractures and movements occur in the soil zone because the material is not cemented together to form a soil layer or beam like the rock strata. Fractures and movements occur during active longwall mining, but can return to a pre-mining state after mining or remain permanently deformed.

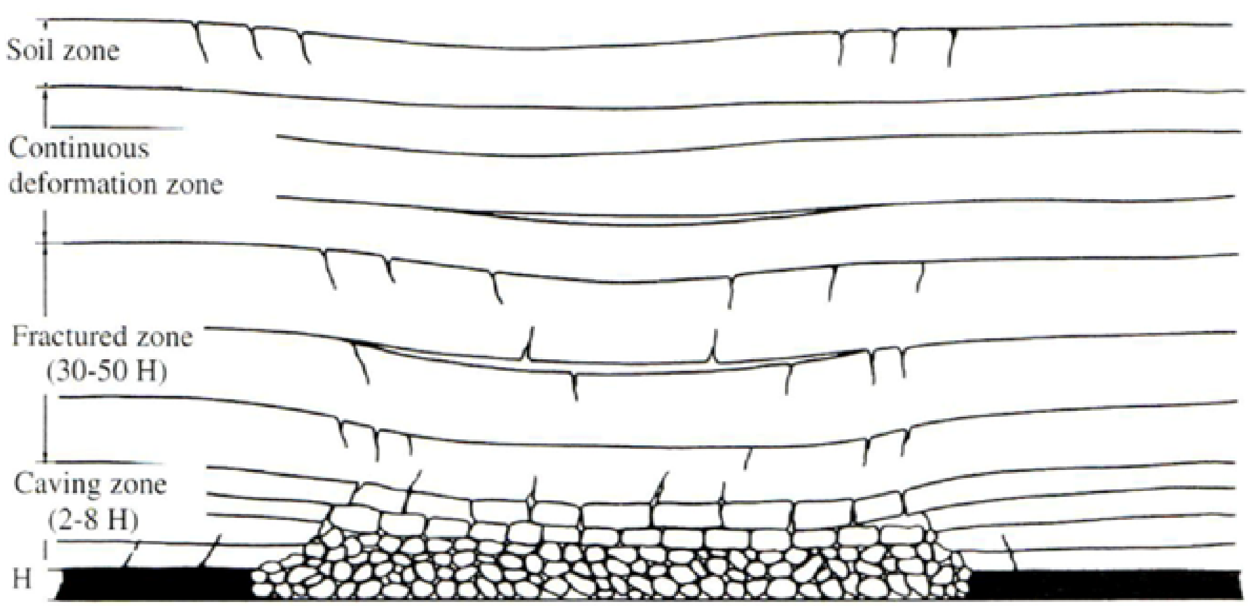


Figure 2.2: Typical trough subsidence showing the unique zones (Peng 2008)

Subsidence in the soil and continuous deformation zone are of primary concern in assessing impacts to water resources. Some ponds and wells will be located within the soil zone. Deep wells can extend to the continuous deformation zone. Since most water sources are located at or near the surface, it is helpful to estimate the subsidence that may occur due to longwall mining. The maximum subsidence for longwall panels in the northern Appalachian region during the 4th assessment period can be calculated with the following equation:

$$\boldsymbol{S_{max} = m \times a} \tag{2-2}$$

where,

- S_{max} = maximum subsidence, ft
- m = extraction thickness, ft
- a = subsidence factor

A relationship between the subsidence factor and overburden was developed by Peng and is as follows:

$$a = 0.6815519 \times 0.9997398^{h} \tag{2-3}$$

where,

- a = subsidence factor
- h = overburden thickness, ft

Gutiérrez (2010) investigated the effects of subsidence on highways in southwestern Pennsylvania using accurate measurements. The study found an average subsidence factor of 0.66 for the region. This subsidence factor results in maximum subsidence values of 3.5 to 4.5 ft for the region.

Horizontal strains are also important with regard to water sources. High strains can cause damage to aquifers or wells. A basic study during the 3rd Act 54 assessment divided longwall panels into three sections: mid-panel, quarter-panel, and room-and-pillar (main, gateroad, and bleeder entries). These sections were defined based on the type of strains expected on the surface. Mid-panel sections should experience minimal strain. Strains in this section will be almost entirely compressional. Quarter-panel sections should experience a mix of compressional and tensile strains. Room-and-pillar sections should experience mostly horizontal strains. These inferences are based on the assumption that the surface topography is flat. However, southwestern Pennsylvania is rugged and flat areas are rare. It was concluded that there was trend between location of a water source to the longwall panel and the probability of an affected water source (Witkowski 2010).

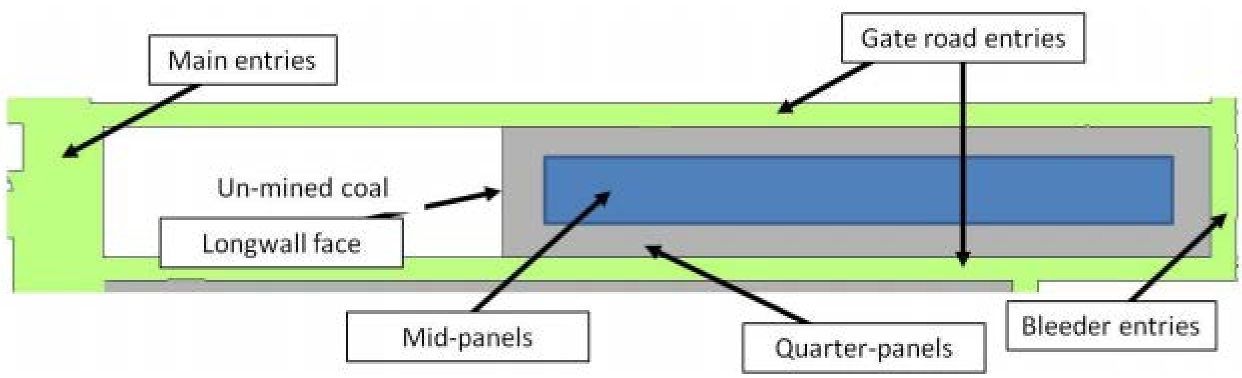


Figure 2.3: Illustration of the 3 sections of a longwall panel regarding strain type (Iannacchione, Tonsor, et al. 2010)

Booth and Greer (2011) studied the impacts on hydraulic conductivity related to active and permanent subsidence. As mentioned in the previous section, hydraulic conductivity is a key parameter controlling flow through an aquifer. The study utilizes MODFLOW, a groundwater modeling software, to estimate changes in groundwater flow when introducing a longwall mine under the system. The study predicts hydraulic conductivity increases in tensile zones and decrease in compression zones. Minimal decreases in hydraulic conductivity are predicted in the compression zones. Conversely, tensile zones can increase hydraulic conductivity significantly. Strains will be discussed in the next section on how minimizing strain can reduce water resource impacts.

2.3 LEGISLATION, GUIDELINES, AND RESEARCH

Legislation regarding the impacts from mining was not thoroughly considered until the early 1940's, when impacts due to a boom in surface mining a decade earlier became apparent. Attention to this issue was delayed during World War II due to the high demand for coal and other minerals. In 1945 the Commonwealth amended its 1937 Clean Streams Act to include acid mine drainage as a regulated form of pollution. Also that year, Pennsylvania passed the Surface Mining Conservation and Reclamation Act, which represented initiative for preventing pollution from surface coal mining (Iannacchione, Tonsor, et al. 2010). Since, several forms of legislation, rules, guidelines, and recommendations were created to address the environmental issues associated with underground coal mining.

One of the most important laws regarding environmental impacts due to mining is the Bituminous Mine Subsidence and Land Conservation Act (BMSLCA) of 1966. Before the passing of the act, mining companies were free to subside the ground of those that had no coal mineral rights during pillar extraction. The act protected surface structures built before 1966 from subsidence, regardless of mineral ownership. Initial suggestions proposed extraction ratios of less than 50% below surface structures for protection. Grays and Meyers (1970) introduced the aspect of an angle of support (angle measured from the vertical) between 15 and 25 degrees to be used for determining a stable area. The use of an angle of support recognizes that subsidence can have an effect on surface features, even if there is solid coal below the feature. Other subsidence prevention methods include construction of underground supports or grouting of abandoned mine openings. Despite the progress the act made, issues on subsidence to surface structures built after 1966 and water resources were not included.

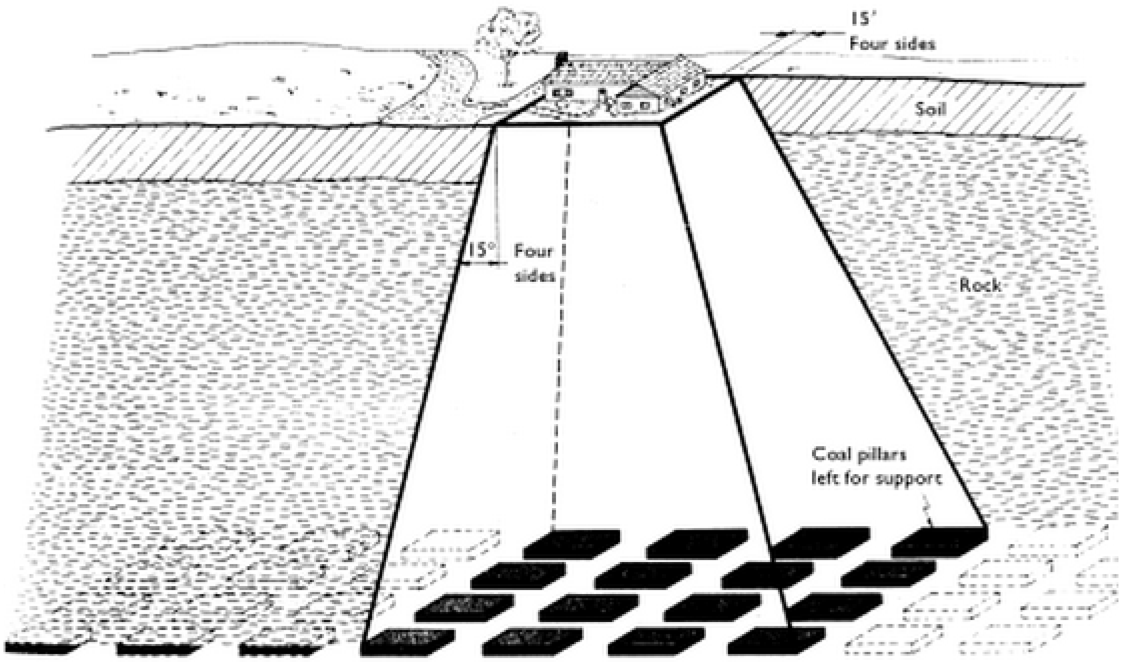
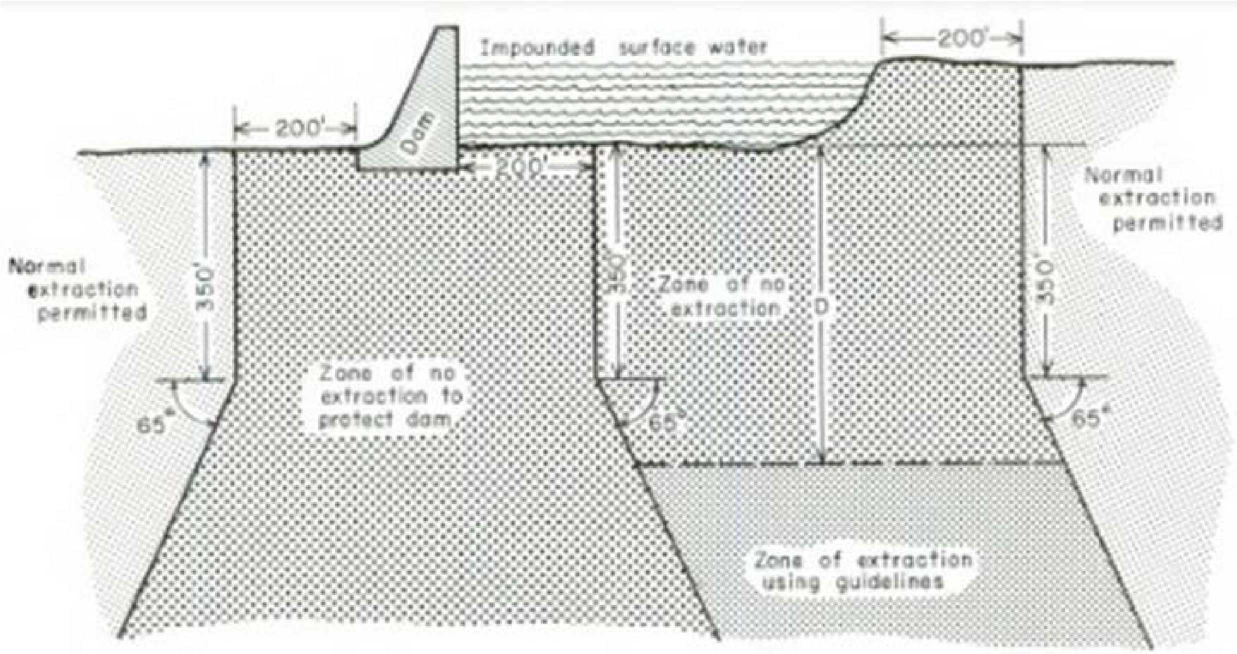


Figure 2.4: Surface support area using angle of support to determine area in mine to be left supported (Gray and Meyers 1970)

In 1980 BMSLCA was amended to address some of the problems that came about concerning the original law. Structures built after 1966 now had to be repaired or the owner compensated if affected by subsidence. The amended act also required companies to minimize the damage to surface structures using best technologies and practices of the current time. The amended act still did not mention concerns with water resources.

Although the amended BMSLCA of 1980 did not include legislation regarding water resources, research on water impacts was ongoing during this period, mostly concerning mining under large bodies of water such as lakes and reservoirs. Babcock and Hooker (1977) presented a U.S. Bureau of Mines publication suggesting guidelines when mining near large bodies of water. The guidelines are similar to those of Grays and Meyers where an angle of 25 degrees is used in order to provide protection to surface bodies of water from subsidence. However, Babcock and Hooker added considerations of geologic materials to their suggested mitigations techniques, including defining a no mining zone within 200 horizontal feet of a body of water at shallow cover (less than 350 ft). This mitigation protects water bodies from the fracturing of the rock in these shallow cover areas. The angle is then applied from this depth to account for the adjacent effects of subsidence.



	D*
Room and pillar	5s or 10t
Panel	3p or 270 ft
Total extraction	60t

* Whichever is larger

Figure 2.5: Guidelines for mining near bodies of water and retaining structures (Babcock and Hooker 1977)

Kendorski (1979) developed a subsidence model that uses an angle of 35 degrees and includes different zones of rock deformation over a full extraction panel. One important aspect of this model is the aquiclude zone. This zone implies that no changes in permeability are found and, therefore, shallow groundwater and surface water do not interact with the mine.

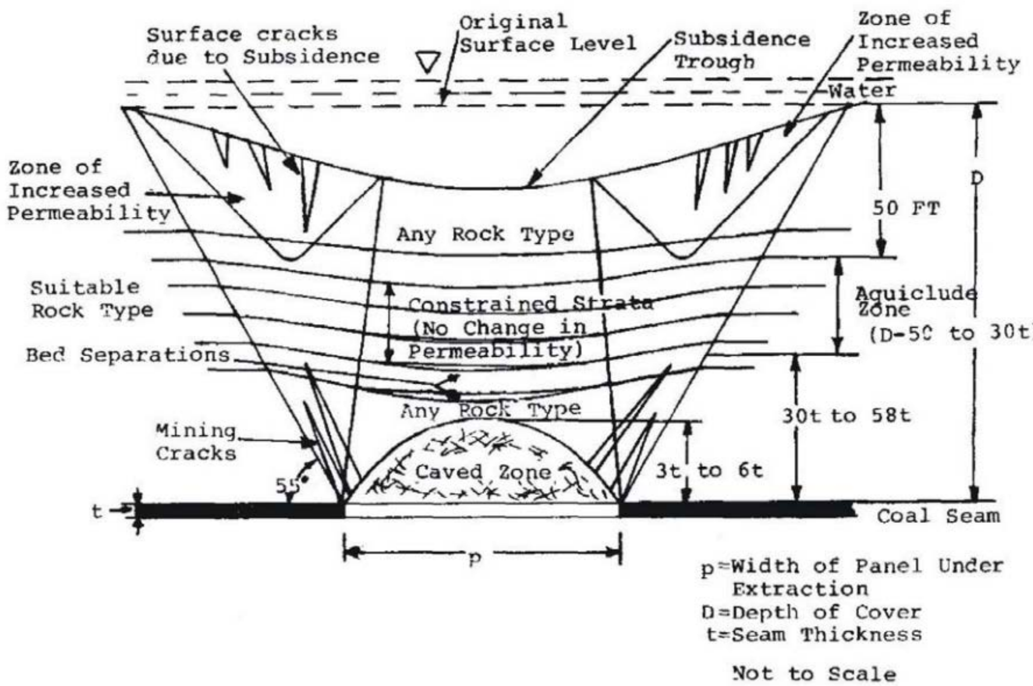


Figure 2.6: 1979 Subsidence model depicting an aquiclude zone (Kendorski 1979)

A similar study done by Singh and Atkins (1983) in the United Kingdom provides many similar suggestions to the Kendorski model. An angle of 35 degrees is used along with the deformation of the overlying strata. The model includes the effects of horizontal displacement and strains from subsidence, an early rendition of Booth and Greer's study. The model is further developed with the introduction of zones of compression and elongation. Initial recommendations for restricted strains were 10 mm/m (10 millistrains) to reduce the risk of ground surface opening in the elongation zone near large bodies of water. These models help to better understand the effects that full extraction mining has on surface waters.

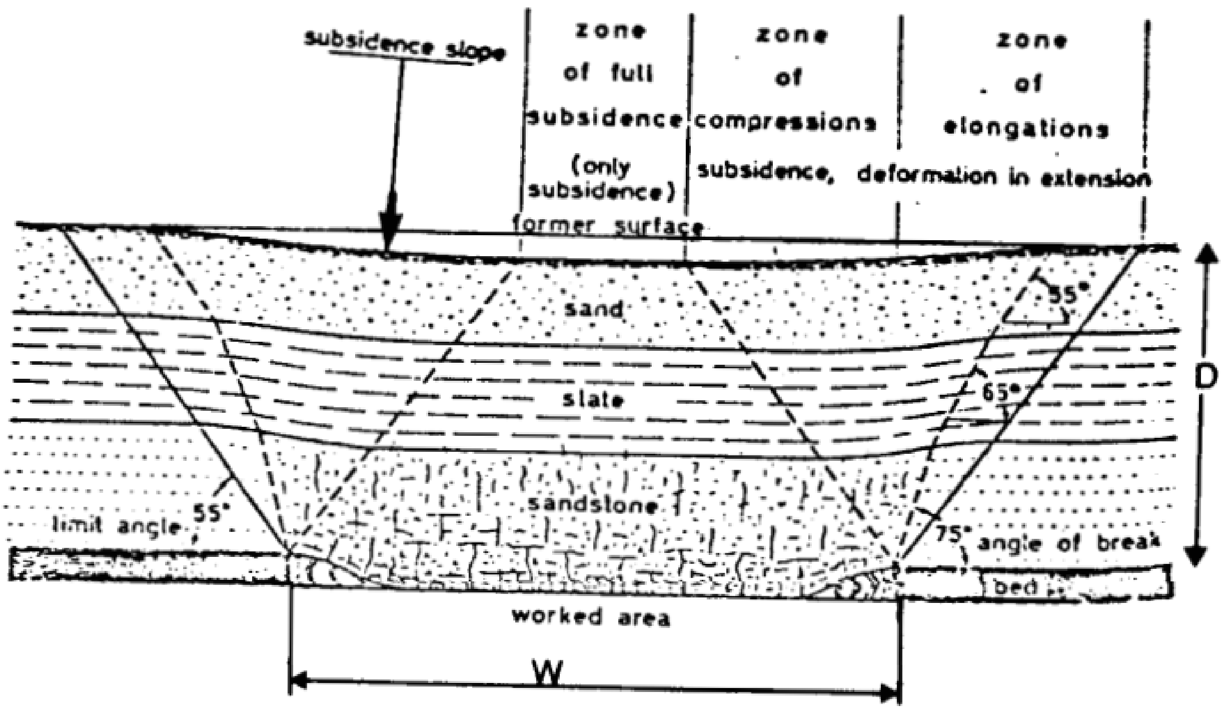


Figure 2.7: 1983 Model depicting surface zones of compression and elongation (Singh and Atkins 1983)

In the late 1980s and early 1990s, longwall mining became a common form of mining in the United States. Its increase in popularity prompted researchers to study the effects of longwall mining on surface and groundwater. Kendorski (1993) developed an advanced subsidence model from the 1979 model to include groundwater flow and water wells. The model depicts temporary and permanent effects to groundwater after longwall mining. Groundwater within the caved and fractured zones will drain into the mine since the rock has been damaged. Groundwater in the dilated and surface zones will experience temporary effects due to increased permeability and storativity of the rock layers. The temporary effects are predicted to return to pre-mining conditions within 2 years once the rock layers have time to settle. Although long term effects were assumed to be likely to return to pre-mining conditions, the short term effects still presented an issue. Loss of water or dry wells provided insufficient water for citizens living over longwall panels. Increased permeability of the aquifers allowed the water to contact metallic and sulfide minerals that could increase dissolved contamination rendering water unsafe or unsavory for drinking. High horizontal displacements and strains can cause wells to collapse, leaving the user without water. These issues presented significant problems for citizens and their water supplies.

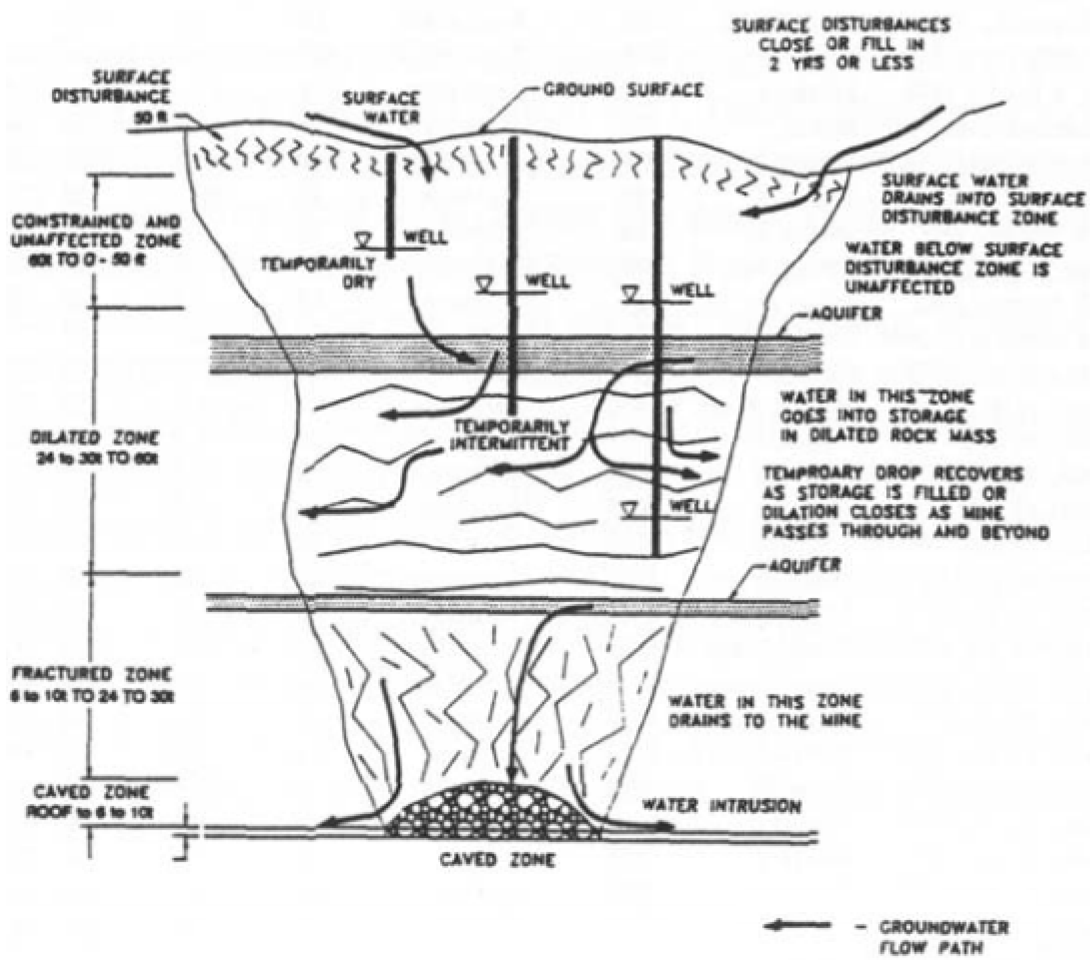


Figure 2.8: 1993 subsidence model depicting groundwater movement through the subsidence zones (Kendorski 1993)

In 1994 Pennsylvania amended its BMSLCA "to provide for the restoration or replacement of water supplies affected by underground mining" (BMSLCA 1994). The amendment is commonly referred to as Act 54. Act 54 contains an abundant amount of text regarding the responsibility that mining companies must take regarding water supplies. The act uses an angle of 35 degrees from the edge of the full extraction area to determine a zone on the surface where subsidence effects are significant. Water supplies residing in this Rebuttable Presumption Zone (RPZ) that are affected will be restored under responsibility of the mining company. The company may dispute responsibility if pre-mining data can be provided that show no significant change in the water quality and quantity. Temporary and permanent solutions include setting up a temporary storage supply of water with the affected water supply owner, hauling water to the owner, connecting the owner to a public water supply, and drilling a new well.

One requirement of the act is that a report be produced every 5 years to access surface impacts from underground coal mining. The Pennsylvania Department of Environmental Protection (PA DEP) conducted the first assessment from 1993 to 1998, California University of Pennsylvania conducted the second assessment from 1998 to 2003, and the University of Pittsburgh conducted the third assessment from 2003 to 2008. The University of Pittsburgh has again accepted to present the forth assessment report, covering the period from 2008 to 2013. The purpose of the periodic report is to assess the effectiveness of controls used to mitigate and restore water supplies as well as monitor effects due to changes in technology.

The key concepts to be taken from the literature regarding effects to water resources due to subsidence are:

1. Water will flow from areas of high head to low head. Water will also flow through a path of least resistance. This can refer to zones of secondary porosity such as open fractures in rock or increases in number of flow paths

2. To illustrate that the surface effects from subsidence extend over a larger area on the surface compared to the area of full extraction, an angle measured from the vertical at the edge of mining is used. The angles most commonly found in research range between 24 and 42 degrees. A 35 degree angle is used by the state for determining RPZ.
3. The zones of subsidence are predicted to affect groundwater based on the properties of the zones. The caved zone will see permanent flow of water into the mine. The fractured zone will experience possible flow into the mine. This zone will also experience greatly increased levels of permeability. The continuous deformation zone will see temporary and possibly permanent increases in permeability. However, the zone will maintain its continuity and, therefore, no interactions of water is predicted with the other zones. The soil zone will experience temporary and possibly permanent increases in permeability. Water in this zone is not predicted to drain directly to the mine. Zones that increase permeability can cause diminution, total water loss, or contamination due to the increase in the pore space of the rock layers. The effects can be temporary or permanent.
4. Horizontal displacements and strains are important in determining surface fractures and structural failures. Excessive displacements and strains can cause slope failures of incompetent soils, tensile failures of rock slopes or highwalls, prominent secondary pathways of surface and groundwater flow, and structural damage to buildings and wells. All features on the surface above an extraction panel will experience dynamic horizontal displacements and strains while only some will experience permanent deformations.

3.0 METHOD OF STUDY

The methods used for this study begin with initial data collection of information related to the influential factors. Data is analyzed through several sources such as hydrogeologic and subsidence theory and modelling. Field visits to sites are made to investigate current processes and collect real time data. Conclusions from the analysis are made based on the trends and influences of the most significant factors.

3.1 DATA COLLECTION

Much of the data is collected from either the PA DEP's California District Mining Office (CDMO) or directly from the companies. The data contains 6 month mining maps and CAD files of the study mines, which include the mine outline, structures, water sources, and coal and surface elevations. The PA DEP's BUMIS (Bituminous Underground Mines Information System) database is also utilized for this study. The database is an organizational tool to aid in tracking impacts reported that potentially are mining related.

Supplemental data and information is also collected during the study period such as subsidence, geologic, and hydraulic monitoring reports. Subsidence reports provide maps of subsidence zones. They also provide information of damaged structures or land damage due to subsidence. Geologic reports contain information regarding the general trends in geology of an area around the mine. Core log data helps define the geology more specifically, especially at an area of interest at a mine such as a stream valley. Geologic logs may also include cross-sections of geology throughout the mine and RQD data that represents rock integrity. Hydraulic monitoring reports include water quality information of residents' water supplies before and during mining to check for variations. Special monitoring wells and piezometers are put in place to monitor groundwater quality and quantity without the effects of pumping that would take place at an owner's drinking well. Data regarding stream flows and quality are also usually in the hydraulic monitoring reports.

3.2 DATA ANALYSIS

To determine the effects associated with underground coal mining and water supplies, an extensive examination of the PA DEP's BUMIS database was utilized. The database contains information regarding reported effects of water supplies. This information includes a locatable position for a water supply, type of effect, date effect occurred, the resolution of the effect, and additional comments. Basic statistical analysis can be computed with this data to determine certain trends and indicators. The initial part of this study focuses mostly on the information in the BUMIS database. The purpose is to determine the wide trends associated with all mines within the study period.

Geographic Information Systems (GIS) software was also used in the study. The GIS software allows for collection and organization of spatial information. Most of the GIS information is collected from the six month mine maps provided by the PA DEP. The maps are first georeferenced using the GIS software. Georeferenceing allows features on the six month mine maps to be given spatial geographic coordinates. Features on the 6 month mine maps are then digitized and organized into a GIS database. Digitized features include water supplies, coal and surface contours, mine outlines, and buffer areas. These digitized features permit for broad applications of spatial analysis.

Information from the BUMIS and GIS databases can be combined to allow for impressive analyses. Spatial information of a feature can be linked to the attributing information from BUMIS, which permits analysis of effects based on locations. This combination of data becomes very useful in determining effects on water supplies because linking effects to locations allows prediction of future effects in similar areas, and these future effects can be quickly addressed. The final part of this study includes three case study mines that are analyzed using the combination of BUMIS and GIS data. The case studies are used to determine the water supply issues within a particular mine, and conclusions should not be extrapolated to other mines without further investigation.

The general format of analysis for the case study mines include a relationship of active and post mining data with pre-mining data. Further spatial analysis includes analytical ground strain and displacement calculations from mining activity which is then compared to influence function software and groundwater movement software to determine changes in hydrology due to mining.

3.3 FIELD VISITS

Field visits are made to gain a better understanding of the activities that take place around mining operations to mitigate impacts to hydrology. Subsidence agents and project engineers accompanied the team on visits for clarification on the work being done. Visits are also made to sites that have been completed for years. This allows for observation of how effective the controls are at returning the hydrology of an area to a pre-mining condition. Another benefit for field visits is the opportunity to collect real time data, which can be compared to previous and other data collections. The following is a brief overview of field visits attended:

- 17 January 2013 (Emerald/Cumberland with Dan Miles) – Observation of spring relocation and subsidence features
- 21 March 2013 (Enlow Fork/Bailey with Ben Dillie) – Templeton Fork restoration at East Finley Park using Rosgen methods and subsidence features
- 17 May 2013 (Cumberland with Dan Miles) – Observation of subsidence in the Maple Run and Pursley Creek watersheds
- 12 June 2013 (Bailey with Josh Silvis, Brian Bensen, and Adrienne Carney) – Stream restoration at Barney's Run using grouting techniques and observation of stream heaving and flow loss on Hewitt Run tributary
- 8 July 2013 (Enlow Fork with Ben Dillie) – Discussion of subsidence features in the Craft's Creek watershed
- 9 July 2013 (Bailey with Brian Bensen) – Observation of alluvial amendment work on Barney's Run

- 20 August 2013 (Blacksville 2 with Anne Hong) – Investigation of stream loss issues at Tom's Run and Blockhouse Run along with observation of previous stream heaving
- 21 August 2013 (Little Toby with Jay Hawkins) – Examination of the Brandy Camp treatment facility and water quality of Mead Run
- 23 August 2013 (Mine 84 with Anne Hong and Brian Bensen) - Observation of alluvial amendment work on Brush Run
- 18 December 2013 (Dora 6 with Jay Hawkins) – Examination of discharges at Hamilton township building, Foundry Run, and Dora 6 fan shaft
- 3 February 2014 (Dora 6 with Bob Dominick) – measurement of water quality and quantity at the Dora 6 treatment pond

3.4 LIMITATIONS

One of the major limitations of this study is the time period in which it is conducted. By being restricted to 5 years, effects that occur within the study time frame may have been impacted by previous mining. Also, many of the effects that occur during the end of the study period have not been given enough time to become resolved. Therefore, some effects that are unresolved may be in the resolution stage.

The information in the BUMIS database offers some limitations. A problem is entered into BUMIS only if a complaint is made. Therefore, the reported effects listed in BUMIS are subjective based on a citizen's willingness to report a problem where underground mining is believed to be the cause.

Time is also a major factor when comparing pre-mining and post-mining data. Much of the post-mining data is limited since the data remains in the collection, quality review, submission, and approval process and is not available for analysis.

Data collection of individual water supplies is also difficult to find. Pre-mining water resource information, such as flow, quality, aquifer type, depth of well, and exact location, is challenging to find due to the age of most wells and springs. Data from the Pennsylvania Ground Water Information System (PAGWIS) is examined but found to be not entirely useful due to the stated limitations, the major one being location since not all drilled wells were geographically logged.

Hydrologic monitoring reports contain data that is usually collected and submitted on a quarterly basis. Information such as stream flows is not represented adequately at these time intervals due to their variation. Variable data such as stream flows are best utilized at smaller time increments to limit variability.

Case study analysis of all 46 mines could not be completed given time constraints. Although the 3 case study mines provide variety to the different types of mining as well as other conditions, the concluded information may be generalized to other mines that fall in a similar category with caution and knowledge of site specific conditions.

4.0 ANALYSIS

This analysis is useful in identifying the large trends associated with the water supply effects associated with underground coal mining. Much of the data comes from the BUMIS database. Within the time period from 21 August 2008 to 20 August 2013, 1,400 effects have been submitted and recorded in the PA DEP's database. These 1,400 effects can be divided into four major types: water loss/contamination, structural damage, land damage, and other.

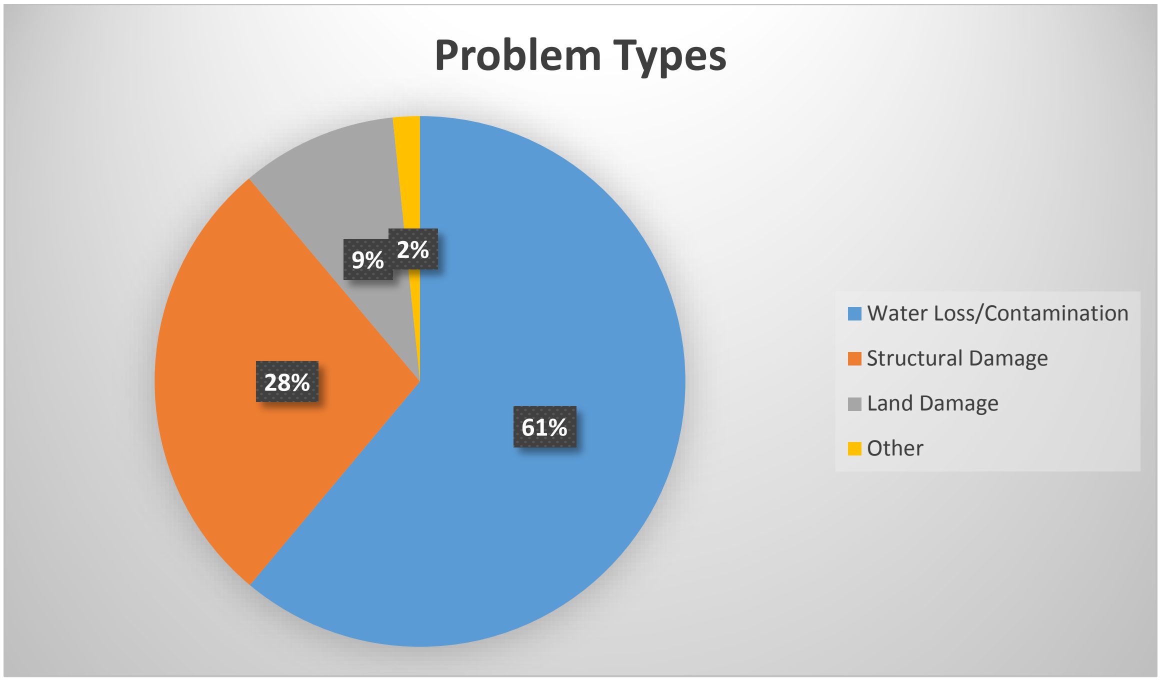


Figure 4.1: Distribution of effects during 4th Act 54 assessment period

Water loss/contamination effects are related to water resources. These effects make up 61% of total effects reported during the reporting period. The large proportion in this category shows the need for mitigation techniques to better prevent impacts to water supplies from underground mining. Wells, springs, or ponds that are felt by the owner to be affected by underground coal mining will fall in this category. Effects in this category are further divided into total loss, diminution, and contamination. These sub-categories are important in determining how a water source has been affected. Total loss or diminution suggests that water has found alternative areas where flow is less restrictive or the aquifer has developed more openings for the water to be stored. Contamination suggests that the aquifer material has allowed water to contact more area within the aquifer, permitting the water to contact minerals in the material that may not have been accessible before mining. Further information on water loss/contamination issues will be discussed later.

The next largest percentage of effects fall into the structural damage category, which includes cracks, breaks, tears, deformations, and misalignments to structural features. Features are further divided into sub-categories of dwellings, garages, barns, sheds, churches, etc.. Some water well features have been classified as structural damage effects since the integrity of the well has been damaged, even if there is no effects with water quantity or quality.

Land damage effects mostly consist of mass wasting and flooding. These effects are mostly due to movements of the ground. Although groundwater can initiate mass wasting events, its certainty is unsure and will not be included in this analysis.

The remaining 2% of effects are defined as other. The other effect type category consists of miscellaneous effects such as methane, noise, air pollution, etc.. These effects will not be analyzed due to their low occurrence and resulting uncertainties in any inference.

4.1 WATER RESOURCE EFFECTS

This thesis is focused on the impacts that mining has on water resources. Therefore, structural, land, and other effects will not be discussed. Table 4.1 summarizes the number of water loss and water contamination effects of the 46 active mines during the study period. It is important to note that 71 water supply effects were reported for mines not active during this assessment period. A total of 784 water supply effects occurred during this assessment period. The table also contains the total area mined during the assessment period. The area is split almost evenly between longwall mines and room-and-pillar mines with a total of over 30,000 acres. The number of water sources located within 1,000 ft of mining are tallied and displayed in the table. This information allows for analysis of water supplies as well as the calculation of columns H, I, and J.

Column H represents the number of water sources located within 1,000 ft of mining per area mined. This is an indication of the density of water sources over a mine. High densities indicate a high number of water sources over a mine of a specified area and vice-versa. Column I represents the percent of water supplies with effects relative to total water sources within the 1,000 ft area of mining. This number can be greater than 1 since multiple effects of a single water source may have been reported during the assessment period. Column J represents the number of water supply effects reported per 1,000 acres mined. On average about 25-26 water supply related effects are reported per 1,000 acres mined.

Table 4.1: 4th Act 54 assessment water supply effects and mine data

A	B	C	D	E	F	G	H	I	J
Mining Type	Mine Name	Water Loss	Water Contamination	Total Water Supply Effects	Total Water Supplies Within 1000 ft of Mining	Area Mined during 4th Assessment Period, acres	Total Water Supplies Per Acre Mined	Percent of Total Supplies Effected (%)	Effected Water Supplies Per 1000 Acres Mined
Longwall	Bailey	58	12	70	650	3709.8	0.175	10.8	18.9
	Blacksville #2	22	6	28	57	1863.3	0.031	49.1	15.0
	BMX	0	0	0	196	566.7	0.346	0	0
	Cumberland	55	6	61	358	2652.9	0.135	17.0	23.0
	Emerald	48	6	54	222	2083.0	0.107	24.3	25.9
	Enlow Fork	141	15	156	704	5901.3	0.119	22.2	26.4
	Mine 84	21	3	24	21	79.5	0.264	114.3	301.7
	Total	345	48	393	2208	16856.5	0.130	17.7	23.3
Room-and-Pillar	4 West	0	1	1	13	799.5	0.016	7.7	1.3
	Agustus	4	2	6	135	255.8	0.528	4.4	23.5
	Barrett	4	0	4	29	120.8	0.240	13.8	33.1
	Beaver Valley	6	4	10	46	205.9	0.223	21.7	48.6
	Cherry Tree	13	6	19	168	920.4	0.183	11.3	20.6
	Clementine 1	51	11	62	90	476.3	0.189	68.9	130.2
	Crawdad	0	0	0	1	223.9	0.004	0	0
	Darmac 2	11	3	14	30	326.4	0.092	46.7	42.9
	Dora 8	2	2	4	41	198.0	0.207	9.8	20.2
	Dutch Run	0	0	0	19	422.0	0.045	0	0
	Geronimo	3	0	3	37	17.3	2.143	8.1	173.8
	Gillhouser Run	2	1	3	61	305.1	0.200	0.9	9.8
	Harmony	1	1	2	6	413.7	0.015	33.3	4.8
	Heilwood	7	3	10	39	382.2	0.102	25.6	26.2
	Horning	1	1	2	16	41.1	0.390	12.5	48.7
	Kimberly Run	18	13	31	172	931.0	0.185	18.0	33.3
	Knob Creek	3	1	4	15	251.5	0.060	26.7	15.9
	Little Toby	8	0	8	12	176.6	0.068	66.7	45.3
	Logansport	24	6	30	269	1079.6	0.249	11.2	27.8
	Longview	2	2	4	8	101.3	0.079	50.0	39.5
	Lowry	0	0	0	16	300.4	0.053	0	0
	Madison	4	1	5	31	651.3	0.048	16.1	7.7
	Miller	0	0	0	3	64.0	0.047	0	0
	Nolo	21	1	22	88	421.9	0.209	25.0	52.1
	Ondo	25	3	28	88	235.4	0.374	31.8	118.9
	Penfield	1	0	1	22	495.3	0.044	4.5	2.0
	Prime 1	1	0	1	7	242.2	0.029	14.3	4.1
	Quecreek	14	1	15	101	745.8	0.135	14.9	20.1
	Rossmoyne 1	38	2	40	70	354.4	0.198	57.1	112.9
	Roytown	5	1	6	81	342.7	0.236	7.4	17.5
	Sarah	1	0	1	7	47.5	0.147	14.3	21.1
	Starford	7	1	8	11	46.6	0.236	72.7	171.8
	Titus	0	0	0	2	40.5	0.049	0	0
	TJS 5	0	0	0	0	1.3	0	-	-
	TJS 6	19	1	20	26	414.1	0.063	76.9	48.3
	Toms Run	2	0	2	85	480.2	0.177	2.4	4.2
	Tracy Lynne	12	7	19	64	347.3	0.184	29.7	54.7
	Twin Rocks	2	1	3	50	473.4	0.106	6.0	6.3
	Windber 78	2	1	3	39	661.4	0.059	7.7	4.5
	Total	313	78	391	1998	14014.0	0.142	19.8	28.3
Total		664	126	784	4206	30870.5	0.136	18.6	25.4

Another analysis involves examining when water supply effects are first reported. Figure 4.2 shows the monthly frequency of water supply effects during the assessment period. The data shows a seasonal pattern with peaks occuring during the late summer/early fall and lows occurring during the late winter/early spring. This pattern is similar to natural fluctuations is stream flow and groundwater levels. A further look at the data reveals that less than half of the water supply effects are resolved as mining related. Therefore, many water loss and water contamination effects may simply be due to natural fluctuations in surface and groundwater. The seasonal trend is also observed for effects due to mining indicating that mining may influence the natural fluctuations. A proportion of the effects that are not due to mining within the last year have not yet been assigned a resolution. The next chapter will focus on specific water supply effects so that a better understanding is made of why some effects are related to underground mining and others are not.

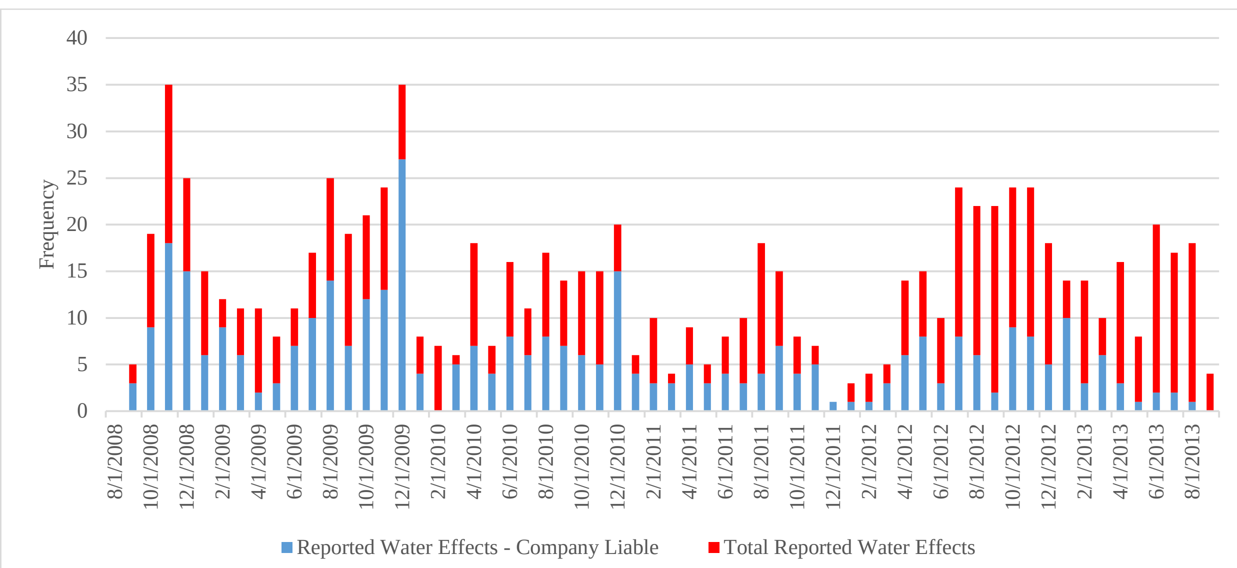


Figure 4.2: Monthly tally of total water supply effects and company liable effects from 4th Act 54 assessment

Mines are analyzed based on the amount of mining that occurred during the 5 year period for the second, third, and fourth assessments. Figure 4.3 and Figure 4.4 represent the number of reported effects per area mined for room-and-pillar mines and longwall mines, respectively. The relationship for both mining types show no strong correlation between reported water effects and mined area. The analysis does show a positive trend for both mining types. However, the poor correlation implies that other factors have influence of water supply effects due to underground mining.

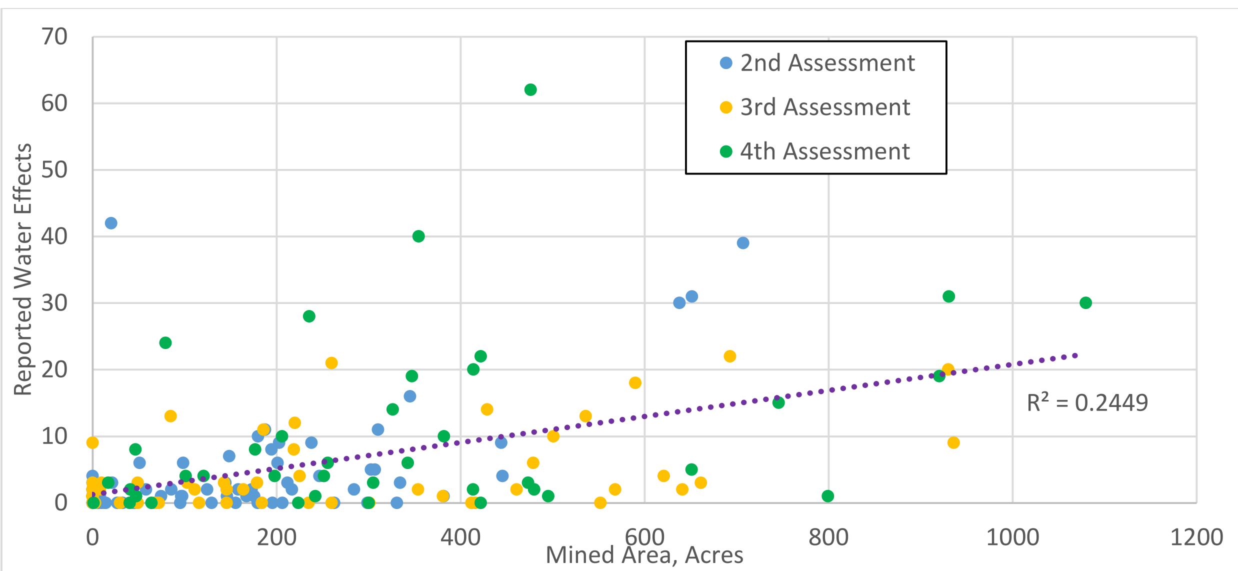


Figure 4.3: Comparison of reported water effects per area mined for room-and-pillar mines

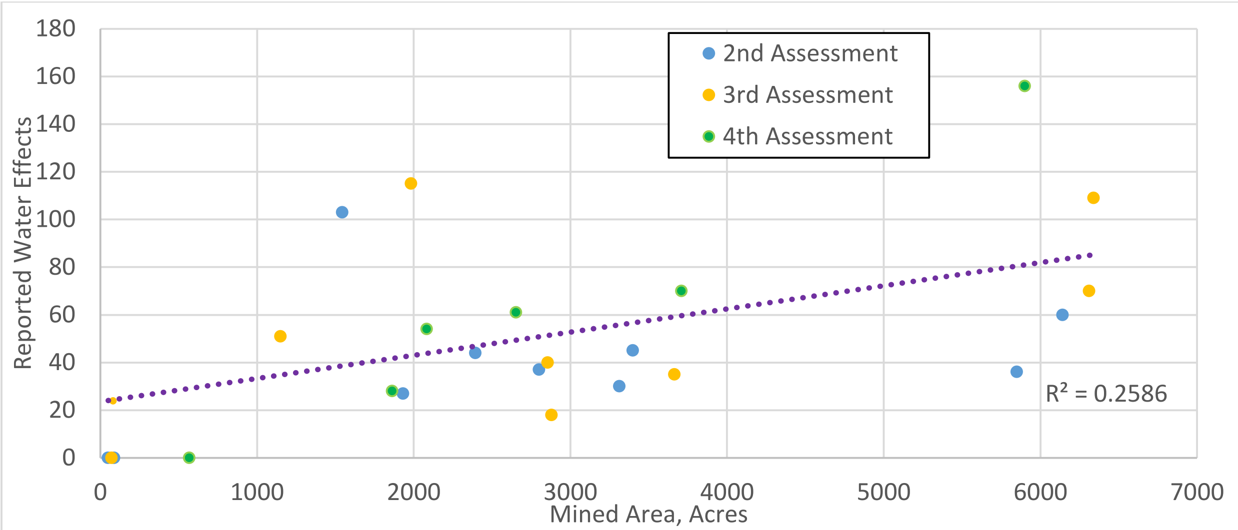


Figure 4.4: Comparison of reported water effects per area mined for longwall mines

4.2 WATER RESOURCE EFEECTS BY MINING TYPE

Mining type is known to be a major factor in effects associated with water resources. Therefore, it is fair to analyze water resource effects within the different categories of mining techniques.

From observation of the totals for longwall mines and room-and-pillar mines, the data shows very similar results. A similar number of water supply effects, total water sources within 1,000 ft of mining, and total area mined are reported. The major difference between the two mining types is that longwall mines cover approximately 7 times more area than room-and-pillar mines. The fact that water supply effects reported per area mined for longwall and room-and-pillar mines is similar indicates that effects are directly related to area mined, although variability can vary greatly depending on several factors related to individual mines. A major factor that affects the difference between mining types is that longwall mines are generally at depths greater than 500 ft while room-and-pillar mines are generally at depths at less than 500 ft. The combination of greater overburdens with longwall mining creates a similar effect on water resources compared to room-and-pillar mining at lower overburdens.

Column J represent the number of water supply effects per 1,000 acres mined. The averages show very similar results between the 2 mining groups. On average 23 water supply effects will occur for every 1,000 acres of longwall mining and 28 for room-and-pillar mining. Variability of this measure does not vary greatly within the longwall mining category, with Mine 84 being a major outlier. The reason is related to the small amount of area mined during this assessment period. This reason continues into the room-and-pillar mining category where mined areas vary greatly, leading to great variations of effects per 1,000 acres mined.

4.3 SOLUTIONS TO WATER RESOURCE EFFECTS

When water supply effects are resolved as being mining related, the first action is to provide a temporary supply of water. A storage tank is brought to the property, and water is either trucked or piped to the tank. The quantity of water stored in the tank is based on the use of the water supply that was affected. It should be sufficient enough to meet the needs of the property owner prior to mining. Once mining has occurred and has relocated to an area where no further effects are likely to happen, a permanent supply is put in place.

Permanent supplies come in several different forms. The primary purpose of the permanent supply is that it should supply the needs of the property owner prior to mining without periodic assistance by the mine operator. If additional operating and maintenance costs are made with the new permanent supply, the operator is charged for the costs over the life of the supply. One method of providing a permanent supply is to drill a new well if a previous one is affected. New wells are usually drilled to greater depths to allow for greater yield. If drilling a new wells is unnecessary, an affected well may be stimulated to provide greater yield. Stimulating a well removes small particles that restrict water flow in the casing and at the bore of the well. If stimulation and drilling fail, connecting the owner to public water is an option. This is usually a last resort since most property owners affected are located a great distance from the nearest public water supply. When springs are affected, if they do not return to a usable condition, then supplemental supplies are made. These supplemental supplies can be in the form of new wells or public water line.

4.4 KEY OBSERVATIONS

The broad analysis provides a holistic look at the water resource effects reported during the 4th Act 54 assessment. Certain patterns are observed and the following key observations are made.

- Mining Methods – longwall mining and room-and-pillar mining show similar trends with the number of effects that occurred. Although the two methods employee different mining techniques, the similarities are due to the offset in overburden thicknesses. Room-and-pillar mines are under low overburdens but employ methods that do not disturb the surface while longwall mines are under deeper overburdens but employ methods that subside the surface causing changes in groundwater.
- Resolutions – As mentioned earlier less than half of reported water supply effects are resolved as mining related. This implies that some water supply effects are due to other occurrences such as natural variations in groundwater levels and precipitation. Most effects are reported during the dry season while the least are reported during the wet season.

The next chapter will identify 3 mines to be analyzed. The analysis will look at the data associated with individual water sources to determine actual causes and effects to water sources.

5.0 CASE STUDIES

The purpose of these case studies is to provide further information about the broad data analysis. Three mines were chosen based on mining type, location, history, and availability of data. The case studies aim to answer why water resource effects occur. However, conclusions made at one mine site may be different than those at another mine site due to varying factors such as geology, hydrology, and mining methods.

5.1 LITTLE TOBY

5.1.1 Background

The Little Toby Mine is located in southern Elk County near the town of Brockport, PA. The mine is owned by Rosebud Mining and was in operation from 2003 to 2011. The mine employs the use of room-and-pillar mining methods with no full extraction areas. The mine is in the Lower Kittanning coal seam.

5.1.2 Reported Water Issues

Within the 5 year assessment period, only 8 water loss issues were reported. However, 5 of those issues refer to the same source. In total 4 individual water supplies were reported to be impacted involving 2 wells and 2 springs.

Spring 1 and Well 1 are located in an area that has not been undermined since 2006. The water loss effects were received by the DEP in late July of 2010. The spring is reported as being a low flow spring but experienced no flow at the time the effect was received. The well is reported as having low yield and is 130 feet deep and the overburden is 245 feet. The flow rate of the well is not mentioned in the BUMIS database. The owner was able to gather water from another spring on the property and use the new source for water needs. No temporary action was taken by the company since the owner had a sufficient supply with their new spring installation. The company did offer temporary support should the spring become dry. Surface mining is also occurring in the area and is within the presumption area. The agent responsible for reporting the issue stated that the area was experiencing lower rainfall than average. Figure 5.1 illustrates the monthly rainfall in 2010 compared to the average monthly rainfall from 2002 to 2012. Data was collected from the National Oceanic and Atmospheric Administration (NOAA 2014) at a rain gage located in Kersey, PA, about 8 miles northeast of Brockport. The data shows a significant period of below average rainfall beginning in June of 2010. In May of 2011, the well returned to pre-mining conditions. Given the conditions that underground mining had not occurred in the area for about 4 years, below average rainfall was noted, the family was able to utilize another nearby water supply, and water quality and quantity returned to pre-mining conditions, the mine was deemed not liable for the reported effects.

Spring 2 is located in an area that was undermined before March 2008. The spring was once used by a cabin by a previous owner. The cabin has since been removed from the property. The current owner reported in late July of 2010 that the spring has no flow. The report was given only to support the condition of Spring 1. The owner had no concern about the condition of the spring since it has not been utilized for several years. The resolution is listed as not an actual problem.

Well 2 is unable to be located based on available information. However, the well is stated to be within the RPZ of underground mining. A diminution effect was reported in July of 2010. A similar effect was stated to occur in 2008 but the property owner did not report the issue. The owner had installed a 300 gallon water tank to allow for more manageable use of the current supply before the effect was reported. The use of the supply was monitored over a period of 9 months by the company as well as supplying temporary water. Should the water supply not be sufficient after monitoring, initial plans include installing a larger water tank and stimulating the well. The stimulation involves pressurizing the well to clean sediment and provide higher yield. The well was stimulated in November of 2010. In October of 2011, the company stated the well recovered to an adequate yield and water quality is similar to pre-mining samples.

The effects submitted to the DEP provide some anecdotal data for responses in the hydrogeology in the area. However, it is unclear whether these effects are caused by mining or natural fluctuations in the hydrogeology. The next section is aimed at studying the hydrogeology of the area and determining influences due to underground coal mining.

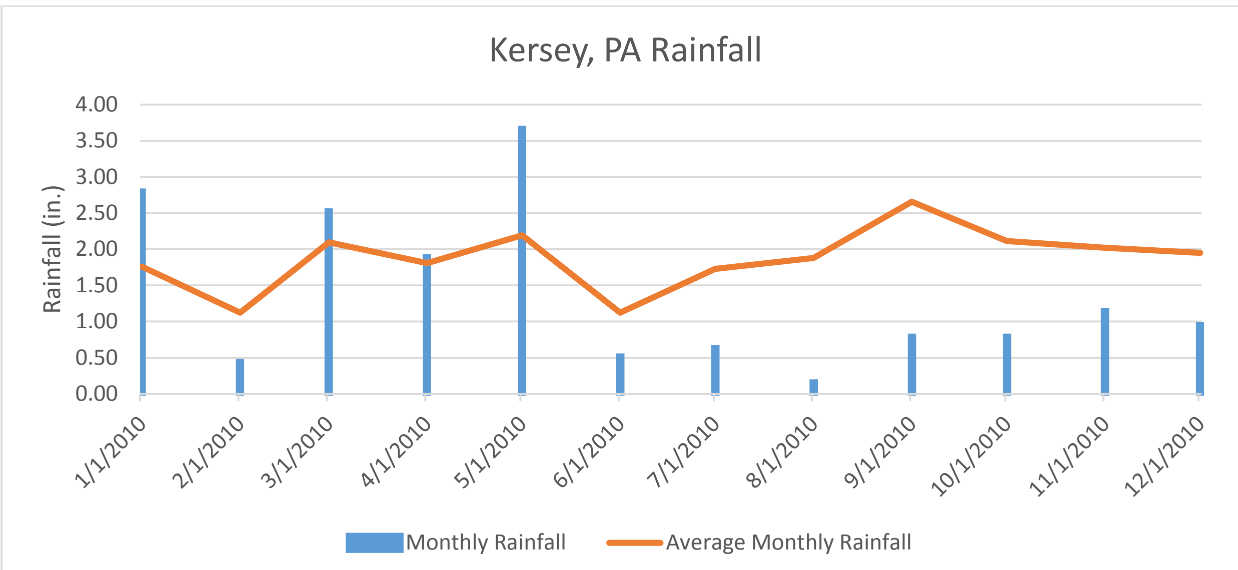


Figure 5.1: Monthly rainfall for Little Toby Mine (NOAA 2014)

5.1.3 Groundwater Analysis

In order to determine the impact of the Little Toby Mine on the hydrogeology, statistical analyses and GIS software are utilized. Statistical analysis is used to compare the local groundwater response with regional groundwater response and pre-mining groundwater levels with post-mining levels. GIS software allows for the inspection of spatial features with respect to mining. GIS also can aid in the hydrogeology by observing areas of surface water flow and groundwater expressions on the surface such as springs, ponds, and wetlands.

The first statistical test is to determine if the groundwater response is affected by underground mining via comparison with groundwater fluctuations in an unmined area. This method is considered valid since groundwater response is greatly attributed to shallow groundwater. A study shows that hydraulic conductivity is inversely proportional to depth to an aquifer (Callahan, et. al 2001). Groundwater age can also be linked with topographic areas such as hilltops and valley bottoms. Groundwater in hilltops is relatively younger than in valley bottoms (Kozar 2012). The well known to be not affected from mining will be the control well. This control well is located in St. Marys, PA, approximately 10 miles northeast of Brockport. The distance from the control well to the monitoring points at Little Toby is considered reasonable since most rain events occur in large cells. This raises the chances that both the control well and the monitoring points will receive the same precipitation. The water level from the St. Marys well is collected daily from the USGS's water resources group (USGS 2014a). The monitoring points include 3 piezometers (PA, PB, and PC) and a monitoring well (MW-1) installed by Rosebud. Data from these monitoring points is submitted to the state on a quarterly basis. It is important to note that piezometer PC was labeled as "Dry" during the entire mining period. The control well and the monitoring points are normalized to an average pre-mining water level to allow direct examination of relative changes in elevations among wells (Figure 5.2). A noticeable drop in the water level of MW-1 occurs in September of 2004. To determine if the drop is significant, a two sample t-test is conducted. The null hypothesis for the test is that the change in monitoring points MW-1, PA, and PB is equal to the change in the control well. The alternative hypothesis is that they are not equal. The results of the test are summarize in Table 5.1 under Hypothesis 1. The test shows that all of the monitoring points respond equally to changes in groundwater when compared to the control well. Even though the probability that MW-1's response to groundwater is equal to the control is lower compared to monitoring points PA and PB, it is still highly insignificant. The noticeable drop in MW-1 can statistically be a natural occurrence.

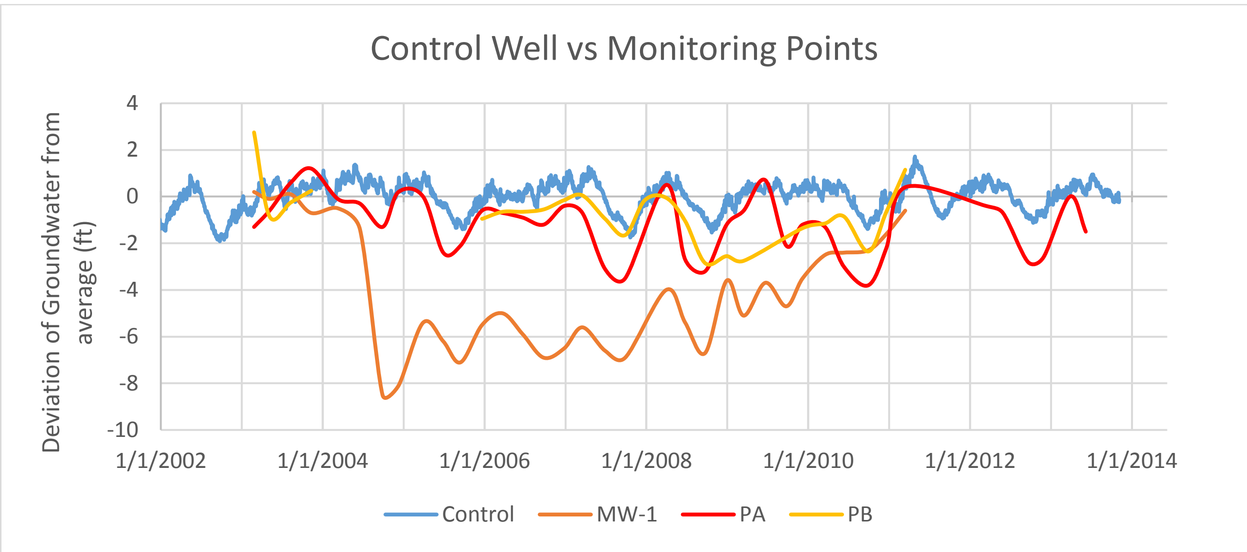


Figure 5.2: Average changes in groundwater level at the Little Toby Mine

Table 5.1: Little Toby groundwater hypothesis tests

Well	Hypothesis 1			Hypothesis 2		
	df	t	$P(T \leq t)$	df	t	$P(T \leq t)$
MW-1	35	-0.1850	0.854	13	8.575	5.19×10^{-7}
PA	49	-0.0758	0.939	3	3.082	0.0270
PB	40	0.0970	0.923	9	0.854	0.2080

The second statistical test is to determine if pre-mining groundwater levels are statistically equal to post-mining water levels. This is again done using the two sample t-test. The null hypothesis is that the average pre-mining groundwater level is equal to the average post-mining groundwater level. The alternative hypothesis is that the average post-mining groundwater level is less than the average pre-mining water level. The decision to make the alternative hypothesis 'less than' instead of 'not equal to' is because there would be no problem if post-mining groundwater levels are higher than pre-mining levels. Only a lowering of the water level will be of concern since it correlates to lower usage of water. Table 5.1 also contains the results of this test. Piezometer PB is found to have no change in water level. Piezometer PA is found to have changed under a 95% confidence interval ($P < 0.05$), but not at the 99% confidence interval ($P < 0.01$). Monitoring well MW-1 shows statistically significant change post-mining. Although only 4 data points were used to determine the average pre-mining water level for each monitoring point, the effect of more data points would only show for piezometer PA given its threshold. This test confirms that monitoring well MW-1 has been affected, but further investigation will determine if it is a result of underground mining.

To understand the cause of the decrease in water level of MW-1, the location of the well is observed. MW-1 is located approximately 500 feet from mining that occurred in 2004. The well is also located less than 500 feet from Mead Run and less than 200 feet from a wetland area. No reports are known that state any changes to Mead Run or the wetland area during that time period. An interesting aspect concerning MW-1 is that it is located 160 feet away from piezometer PA. The proximity of these monitoring points should show their water levels to be nearly identical, but MW-1 shows a difference of nearly 8 feet compared to piezometer PA. A unique factor concerning the difference in the monitoring points' water levels is the effect of surface mining.

The area around the Little Toby mine has been known for surface mining for many years by the local communities. From observation of Little Toby's environmental resource map, surface mining is indeed prevalent in the area. Closer inspection of the map reveals an important factor in the cause of MW-1's water level decreasing. MW-1 is located in an area that was once surface mined. The date of surface mining in this area is unknown. However, surface mining does explain the decrease in MW-1's water level. The disturbance of the surface causes a decrease in the groundwater level because the excavation causes a cone of depression to for along the high wall. Even after the area is returned to original contours during reclamation, the water level remains low due to the increased porosity of the returned rock and soil. The water level of MW-1 eventually returns to a pre-mining level once the soils have had time to settle. Piezometer PA may have also sensed the effects of surface mining, which explains the significantly different post-mining groundwater level. It is unlikely the drop is related to the Little Toby mine due to the low hydraulic conductivity of the shale overburden.

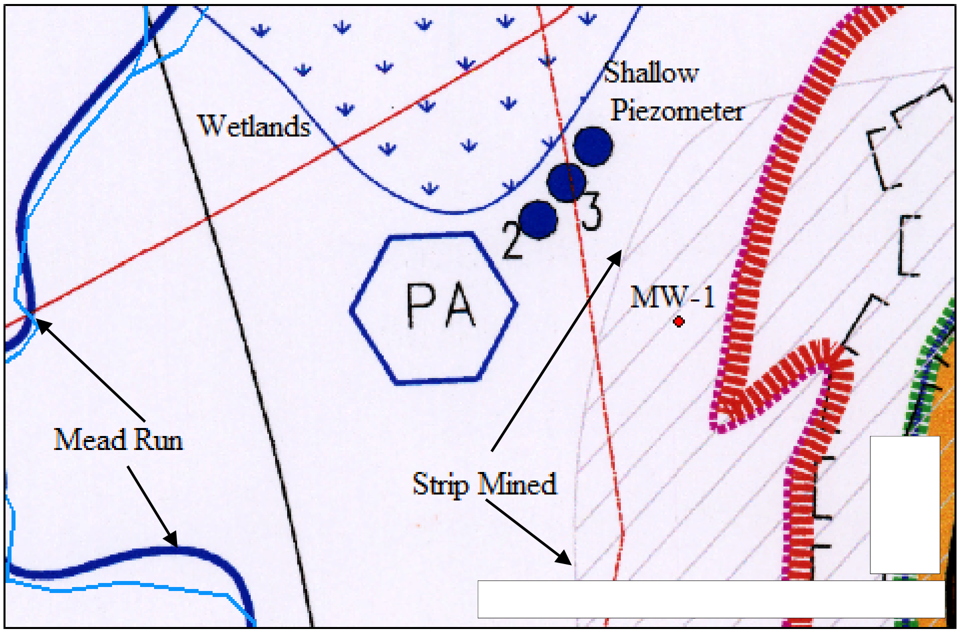


Figure 5.3: Location of Piezometer PA and MW-1 with respect to surface mining

Deeper aquifers are analyzed to understand the effects of mining since not all potable water is located in surface aquifers. Figure 5.4 illustrates the shallow, intermediate, and Lower Kittanning groundwater elevations from piezometer-PA. The shallow groundwater is measured to bedrock, approximately 65 ft about the Lower Kittanning coal seam. The intermediate groundwater level is measured in the Middle Kittanning coal seam approximately 55 ft above the Lower Kittanning. The first trend noticed is that the Lower Kittanning groundwater level experiences the greatest drop when mining begins. The Middle Kittanning groundwater level also experiences a significant drop, but the drop is less than that seen in the Lower Kittanning. A second trend observed is both groundwater levels are rising once the mine has closed. The Middle Kittanning is within 1 ft of pre-mining elevation while the Lower Kittanning is within 2.5 ft as of June 2013.

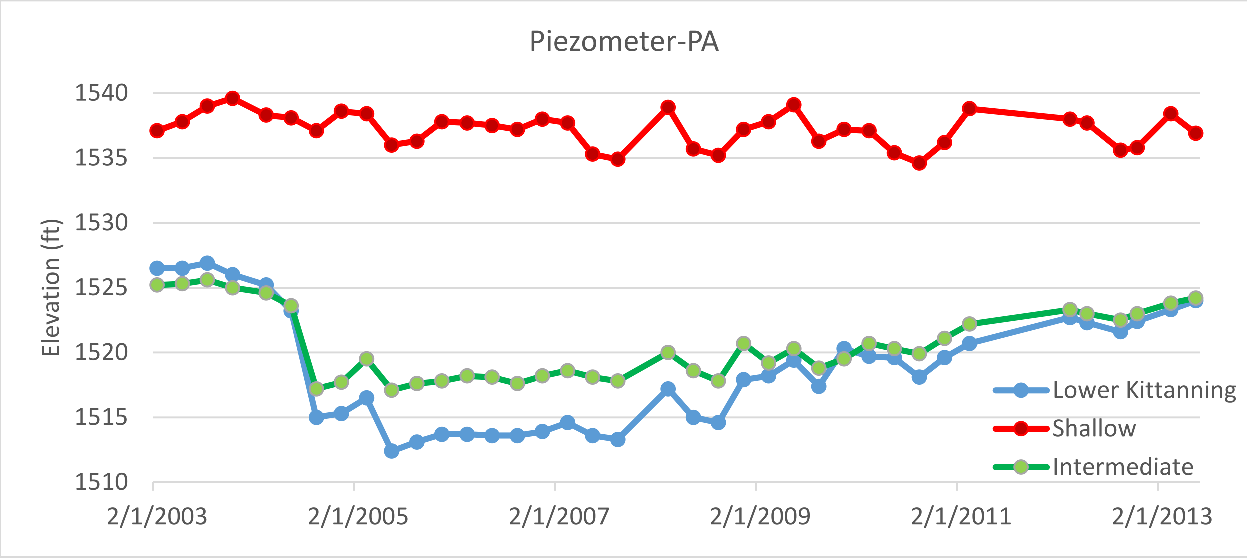


Figure 5.4: Shallow, intermediate, and Lower Kittanning groundwater elevations

A concise representation of the readings collected by all piezometers is summarized in Table 5.2. The trends seen for piezometer-PA are also noticed for the others. As distance from mining increases, groundwater loss decreases. This entails that mining impacts of groundwater effects decreases as a water supply is farther from mining. Also, as the distance between an aquifer and the mined coal seam increases, groundwater loss decreases. This trend shows a contrary relationship of mining and groundwater loss when compared with the RPZ. The RPZ relationship states as the vertical distance from mining increases, the horizontal distance increases. In reality, as the vertical distance from mining increases, the horizontal distance decreases since there is a vertical strata barrier between the aquifer and the mine. This trend also follows data from case study mines Genesis 17 and Keystone East, which are similar to Little Toby, from a study done by Himes, Jr. in 2014.

Table 5.2: Summary of Groundwater Loss for Little Toby Piezometers

Piezometer	Distance from Mining, ft	Shallow		Upper Kittanning		Middle Kittanning		Lower Kittanning	
		Maximum Groundwater Loss, ft	Distance above LK coal seam, ft	Maximum Groundwater Loss, ft	Distance above LK coal seam, ft	Maximum Groundwater Loss, ft	Distance above LK coal seam, ft	Maximum Groundwater Loss, ft	Distance above LK coal seam, ft
PA	660	2.5	65	-	-	5	55	12	0
PB	420	2.8	70	-	-	-	50	14	0
PC	180	-	230	23	140	40	50	70	0
MW-1	450	8	95	-	-	-	-	-	-

5.1.4 Key Observations

The Little Toby mine shows little effect on the hydrogeology in the Brockport area. A majority of the effects stated at the Little Toby mine can be attributed to below average rainfall and drought conditions. Important factors identified at the Little Toby mine include:

- Room-and-Pillar Mining – most room-and-pillar mines have been show to not have significant effects on shallow groundwater. A majority of water sources in the vicinity of a room-and-pillar mine will not experience an effect. Piezometer data at this and other mines have shown no significant changes in shallow groundwater levels during mining. Deeper aquifers do show an influence from active mining but return to previous levels once mining ceases. These trends are found for room-and-pillar mining at locations that are directly undermined with greater than 200 ft of overburden. Room-and-pillar mining at shallower overburdens should be further investigated.

- Surface Mining – the Little Toby mine is also located in an area of surface mining. Surface mining does disrupt groundwater in the area of mining since the surface is disturbed. Even after surface mining, groundwater movement and quality is different because lose material now replaces intact rock. The monitoring wells at Little Toby demonstrate how groundwater levels can change significantly when comparing an area that has been surface mined to one that has not.
- Geology – much of the geology overlying the Little Toby mine consists of shale. Assuming primary porosity, shale's hydraulic properties tend to be relatively low compared to other rock types such as sandstone or limestone, which is why shales make poor aquifers. Vertical hydraulic conductivities also tend to be lower than horizontal hydraulic conductivities. Since the vertical interaction between shallow groundwater and the coal mine is negligible, variations in shallow groundwater levels cannot be mining induced.

5.2 ENLOW FORK

5.2.1 Background

The Enlow Fork Mine is located in southwestern Washington County. The mine opened in 1990 and is currently operating. It mines the Pittsburgh 8 coal seam and employs the use of longwall and room-and-pillar mining methods. To date more than 200 million tons of coal have been removed from the mine, covering an area of over 42 mi^2 (MSHA 2014).

5.2.2 Reported Water Issues

Within the 5 year assessment, 156 water issues were reported. The water related issues include 141 counts of water loss and 15 counts of water contamination. Water loss issues tend to represent a high percentage of total water supply issues for longwall mines because of the large areas of subsidence that take place.

Locating the features with water issues proves to be a difficult task. Most of the features that are listed as effects in BUMIS have unique identifying names that can easily be matched with the identification of the same feature on a 6 month mine map. However, approximately half of the effects listed in BUMIS related to the Enlow Fork Mine lack these unique names. Therefore, water supplies were placed in the groups of found, not found, and repeated.

Only 73 of water supply effects were able to be located, less than 47%. Of the water supply features that were able to be located, 7 lie farther than 1,000 ft from mining during the assessment period. However, 3 of the 7 have been undermined from previous mining. Sixty-two of the 73 located effects are within the RPZ, as are 538 water sources with unreported effects. The company is liable for the 10.3% of water sources reported since they lie within the RPZ unless the company successfully refutes the reported effect.

A total of 79 features are listed in the not found category. Features that are not found could not be located for various reasons. The most common is that the property on which the water source is located could not be identified. The property may be located beyond the extent of the 6 month mine maps. Properties can also change through time where one property can be broken into smaller parcels. Another problem that is significant to the Enlow Fork Mine is that the mine maps contain two different parcel identifications. One identification is used for collecting taxes on parcels of land and the other is a company made identification system. The BUMIS database collects parcel information based on tax maps. Therefore, parcels identified using the company identification system cannot be located. A second limitation in locating water sources is a single parcel may have multiple water sources and the impacted water source may not be specified in the BUMIS database. Since the water source cannot be identified, it is listed as non-distinguishable, meaning the affected feature can only be identified to within a parcel. A third reason includes parcels that are stated as having a water supply effect but no water supply exists on the parcel. This may be related to parcel boundary changes. It may also be related to a mislabeling of information whereby an owner may report an effect on one property parcel but lives on another. The owner's occupied property is then labelled instead of the property with the effect. Features that cannot be located are not included in any spatial analysis.

Repeated water supply effects include features that are reported more than once. Only 4 counts of a repeated water supply are listed in the BUMIS database involving 3 features.

The PA DEP has 36 unique classifications for resolutions of affected water supply features. Relating to water supply effects at the Enlow Fork Mine, 11 unique resolutions are found. These 11 resolution types can be distributed into 3 main categories: company involvement, no company involvement, no resolution.

Of the 156 total water supply effects, 95 show direct company involvement. Initial involvement usually results with a temporary water supply set up at an owner's property. A temporary water supply consists of a water buffalo or storage tank that is connected to the owner's home. Water is then trucked or piped to the storage tank to guarantee a sufficient supply of water for the owner. Once a temporary supply is in place, a permanent supply must be planned once mining has passed through the area. Plans to install a permanent water supply include stimulating an existing well, drilling a new well, or attaching a public water line to the owner's supply.

Resolutions that show no company involvement are usually related to the distance to mining. Some reported issues can be miles from nearest mining. Since these problems are presumed to not be due to mining because of the distance, the issue regarding the water supply can be attributed to natural events, improper maintenance, or normal wear and tear on equipment and materials.

The remaining 43 effects have yet to be resolved. Resolution times can take anywhere between a day to several years depending on the situation. Quick resolutions will occur if the company has already made an agreement with the property owner. Lengthy resolutions will occur if an effect requires extensive action or has ambiguity. Extensive action can include drilling wells with a period of testing to make sure the well is sufficient for the owner's use. Ambiguous effects cause disagreements between different parties, usually the company and the state. These effects can result in legal action, consequently taking years until a final decision is reached.

The following section will examine the hydrogeology of the area around the Enlow Fork Mine. The analysis will be similar to the Little Toby case study. However, time will be an important variable since mining occurs quickly at different points near observation wells and piezometers.

5.2.3 Groundwater Analysis

A similar groundwater analysis compared to the previous case study is also performed for the Enlow Fork Mine to determine the mine's interaction with the hydrogeology. Again statistical analysis and GIS software are used. Subsidence analysis will also be conducted in the next section. Subsidence modelling software will be used to understand the amount of strain the ground surface is experiencing after subsidence has occurred.

Like the previous case study, a control well is chosen that has no influence from mining. The control well is located in the community of West Finley and is located approximately 5 miles from the monitoring well wished to be studied. Water levels are collected daily from the USGS's water resource group (USGS 2014b). Two piezometers are utilized in this analysis. Piezometer-HS is located at the end of the F18 panel. Piezometer-FS is located on the edge of the F22 panel. No piezometers were found to be located within a panel. The locations of the piezometers are important in studying the reaction of groundwater as a longwall panel approaches a water source and passes by a water source.

Piezometer-HS is the first analyzed. Data for this piezometer is collected on a quarterly basis, approximately. Data includes water elevations for shallow groundwater from March 2008 to February 2013. Shallow groundwater includes water below the surface and extends downward to a confining rock layer. Shallow groundwater piezometers are typically less than 20 ft in depth but can be deeper. Figure 5.5 displays the average change in groundwater levels for piezometer-HS and the control well. Also displayed is the distance longwall mining is from piezometer-HS. The distances are measured to the 5 nearest longwall panels F16 through F20. Also, only the distances closer than 2,000 ft are displayed. Mining farther than 2,000 ft is assumed to have an insignificant effect on the piezometer.

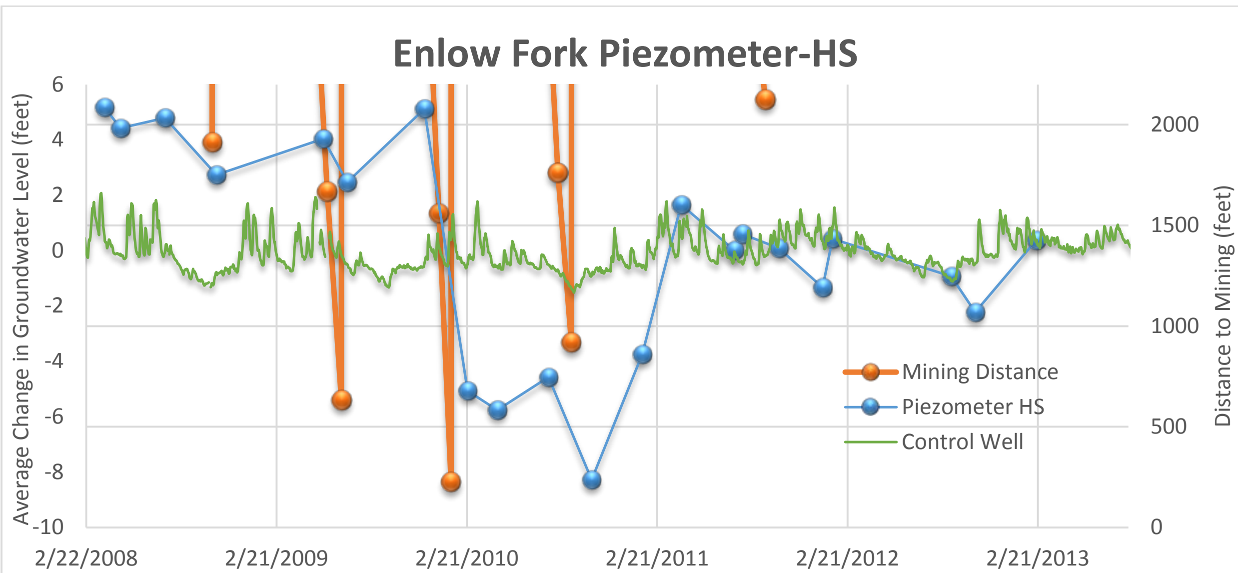


Figure 5.5: Average change in groundwater levels and distance to mining for piezometer-HS

Two observations are made from the graph. The first is the difference in the average groundwater level of piezometer-HS from pre-mining and post-mining measurements. The pre-mining period is defined from March 2008 to January 2010. The post-mining period is defined from March 2011 to February 2013. The intermediate period is defined as active mining. A statistical t-test is done to compare the groundwater levels of both piezometer-HS and the control well from pre-mining to post-mining. The null hypothesis for both tests is that the pre-mining and post-mining average groundwater levels are equal. The alternative hypothesis is that they are not equal. Table 5.3 summarizes the results of the test. The results show that the control well average groundwater level shows little variation from the pre-mining average to the post-mining average. Piezometer-HS shows statistically no difference in the pre-mining and post-mining groundwater level measurements. However, the average difference is approximately 4 ft. No statistical difference can be related to the number of measurements taken. A greater number of measurements would likely decrease the variance and show a statistical difference. However, the given data concludes no significant difference in the pre-mining and post-mining groundwater levels for piezometer-HS.

Table 5.3: Enlow Fork piezometer-HS statistic test

Well	**df**	**t**	**P(T≤t)**
Control Well	716	-0.006820	0.9945
Piezometer-FS	5	1.4706	0.1069

The second observation is the 10 ft decrease in the groundwater level of piezometer-HS between 2 December 2009 and 23 February 2010. The control well shows fluctuations in groundwater levels maintained within ±2 ft from the average. The drop occurred during the time when mining was within 250 ft of the piezometer. A few months after mining advances to the F19 panel, the groundwater level shows a recovery period. As mining approaches within 950 ft of the piezometer, a 4 ft drop in the groundwater level is measured. The control well shows a maximum change in groundwater levels of 0.5 ft during this same period. Back-tracking to the F17 panel, which comes within 650 ft of piezometer-HS, the groundwater level for both the piezometer and the control well show a similar increase in depth to water. The 10 ft drop is found to be statistically significant at the 99% confidence level, and the decrease can be attributed to the approaching F18 longwall face. The drop that occurs as the F19 panel approaches is insignificant. However, the drop may possibly be influenced by the proximity of both the F18 and F19 panels since the F17 panel experienced a similar response when compared to the control well, despite F17 being closer to piezometer-HS than F19. Once the F19 panel has been mined, no mining appears within 2,000 ft of the piezometer. During this time, piezometer-HS experiences a 9.7 ft recovery in the groundwater level over a 6 month period. After this recovery period, the groundwater level appears to stabilize over a 2 year period. Data extending beyond this time will help determine the long term effects on the groundwater level at piezometer-HS.

Water quality is also measured during the same time period. The measures graphed in Figure 5.6 include suspended solids, metals, and sulfate levels. These measures are chosen since they are considered good indicators for changes in hydrology by members of industry and government. They can also be attributed to health and safety of drinking water. A look at the quality measures show similar trends to groundwater level changes relative to mining.

Observation of suspended solids in piezometer-HS show a significant increase during the passage of the F18 panel and also the F19 panel. The F17 panel shows no indications of impacts although mining is closer than the F19 panel. A theory is that increased levels of suspended solids can be related to increased flow velocities of groundwater. Higher velocities will keep particles suspended in the groundwater before settling. The higher velocities in the groundwater can be induced by mining by opening pore spaces in the soil and rock aquifers. Since larger pore spaces allow for less restricted flow of water, flow velocities increase. Flow velocities can also be altered by changes in groundwater head. The local drop in the groundwater level at piezometer-HS can cause the flow velocities around the piezometer to increase. The quick recovery of suspended solid levels in the groundwater indicates that pore space quickly reaches an equilibrium similar to pre-mining conditions and that the head differences between the local and regional groundwater levels decrease. However, current data cannot confirm this theory. Measurements of groundwater levels within close proximity of the affected piezometer are needed to determine changes in hydraulic gradient and velocity.

Metal concentration levels also show a similar trend because the concentration of metals and suspended solids could be strongly correlated if the aquifer is not filtered. No significant changes are observed until the passage of the F18 panel. Residual observations are also viewed as the F19 and F20 panels pass. Again, a combination or pore space and head changes can be assumed since local spikes in the data are observed rather than long term changes and trends. Iron shows the most sensitivity to these changes. Aluminum reacts similarly to iron as the F18 panel passes but has less of a residual effect during the passage of the F19 and F20 panels. Manganese shows little effect to the passage of the longwall panels. All metals return to pre-mining conditions once mining has passed.

Sulfate levels show a different trend compared to suspended solids and metals. Sulfate levels experience a small, but insignificant increase during the passage of the F17 panel. A significant increase is noticeable after the passage of the F18 panel. Unlike suspended solids and metals, sulfate levels do not experience a quick recovery period. This trend results in two possible theories. One is that sulfate levels are more susceptible to groundwater volumes than velocities. The increase in sulfates correlates to the decrease in groundwater levels. Since there is less groundwater in the piezometer, the sulfate concentration increases. As the groundwater level rises, sulfate levels show a decline indicating that the concentration of sulfates in the groundwater is due to dilution. Dilution also explains why sulfate levels do not return to pre-mining conditions since the groundwater level does not return to pre-mining measurements. Two is that sulfate levels experience the same mechanism of increased flow paths and pore spaces that causes an increase in suspended solids and metals. However, sulfates such as sodium sulfate (K_{sp} = 21.8) and calcium sulfate ($K_{sp} = 4.93 \times 10^{-5}$) are highly soluble and will not drop out of solution as easily as metal precipitates, such as iron(II) hydroxide ($K_{sp} = 4.87 \times 10^{-17}$), iron(III) hydroxide ($K_{sp} = 2.79 \times 10^{-39}$), and aluminum hydroxide ($K_{sp} = 3.0 \times 10^{-34}$) because sulfate has low sorption. Although the increase in sulfate levels is significant compared to pre-mining measurements, the concentrations are below a common sulfate concentration of 50 mg/L in the region and well below the Pennsylvania drinking water standard of 250 mg/L.

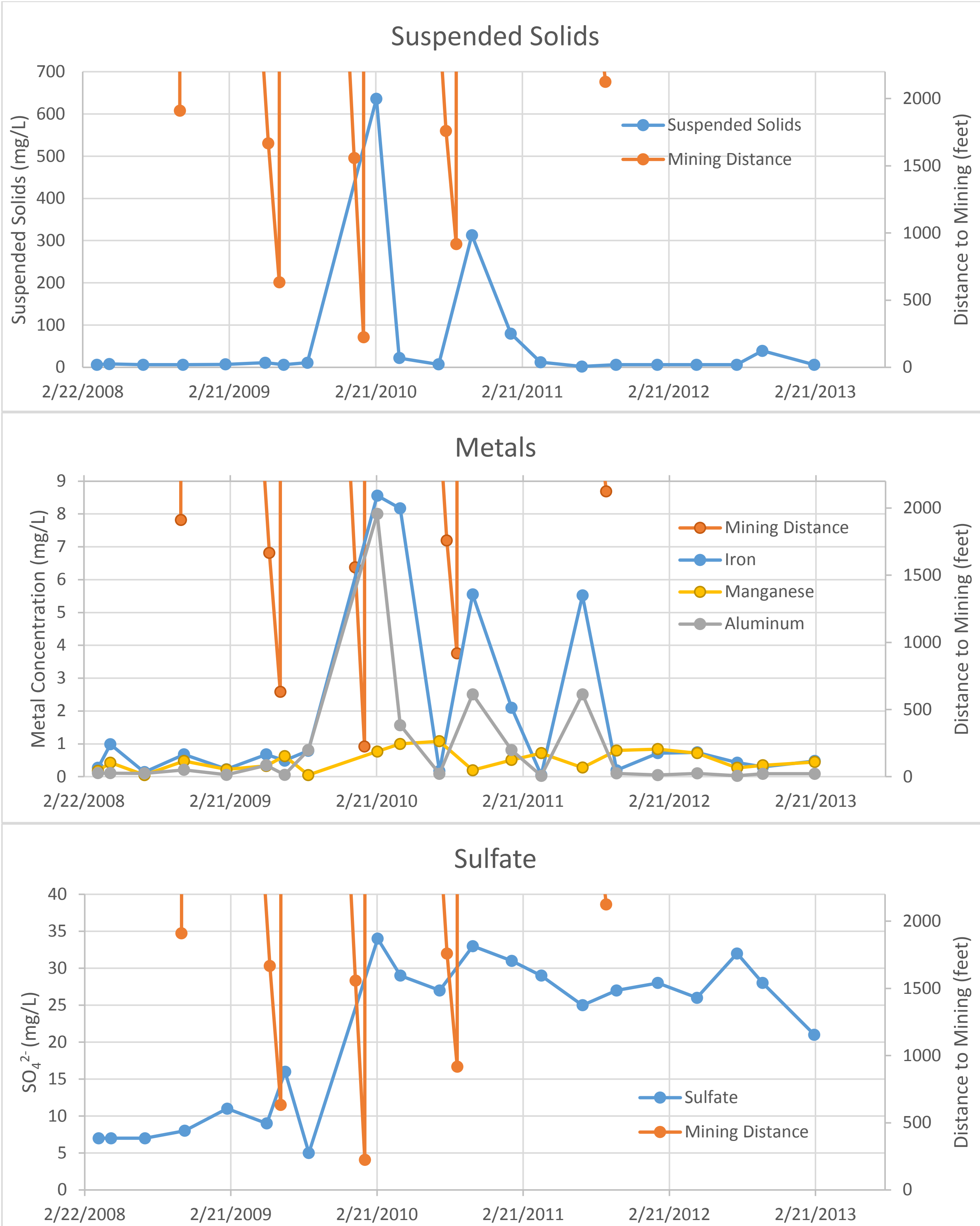


Figure 5.6: Groundwater quality measurements at piezometer-HS

The second groundwater monitoring point is piezometer-FS. Piezometer-FS is similar to piezometer-HS in construction and data collection. The only difference is that piezometer-FS is located at the edge of the F22 panel and experiences different effects compared to piezometer-HS. Figure 5.7 represents a similar graph of groundwater levels and proximity to mining.

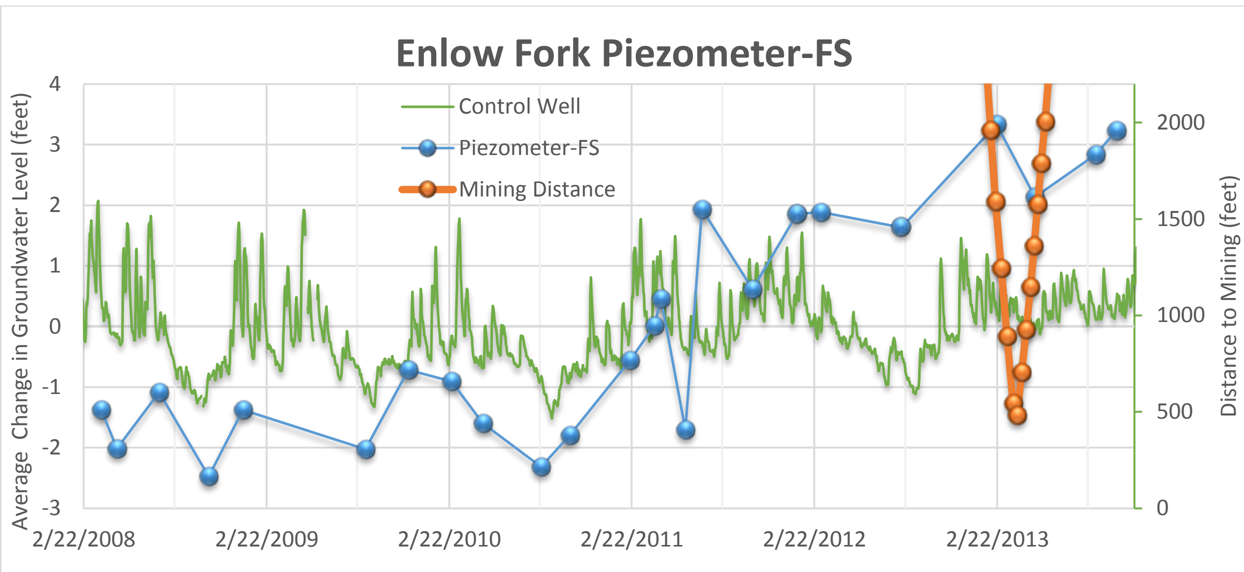


Figure 5.7: Average change in groundwater level and distance to mining for piezometer-FS

Much of the data represents the pre-mining condition of piezometer-FS before the F22 panel approaches. The data reveals that the groundwater levels at the control well and piezometer-FS mimic each other closely for a 3 year period. Piezometer-FS then shows a steady increase in the groundwater level while the control well remains relatively consistent. This change in the groundwater level illustrates the effect that local groundwater levels have compared to regional ones. A closer observation of the location of piezometer-FS reveals that it is located on a hill-top. Hill-tops are areas of groundwater recharge. Piezometer-FS is also not located near any areas of groundwater discharge. The increase in groundwater level can be attributed to increased groundwater storage in the area of piezometer-FS since the area experiences more recharge than discharge. The increased recharge can be seen in the control well measurements taken in 2011. The summer period usually displays groundwater levels below average by greater than 1 ft. The summer of 2011 shows the groundwater level only dropping below average by about 0.5 ft, indicating a wet year. As the F22 panel approaches in early 2013, no significant changes are observed in the shallow groundwater level of piezometer-FS, even when the panel is closest at 483 ft. However, the post-mining groundwater level is significantly higher than the pre-mining level.

Water quality is again observed in relationship to groundwater levels. The trends are quite different when compared to piezometer-HS. Suspended solids may show a slight increase following the passage of the F22 panel compared to pre-mining data. The level does drop shortly after mining. The increase and quick recovery is similar to the reaction of suspended solids at piezometer-HS. One noticeable data point occurs in May of 2009. This significant change can be assumed to be either an error or due to some event that occurred within the area of piezometer-FS. Mining at this time was over 7,000 ft away. Therefore, mining cannot be the cause of the spike.

Metal concentrations do not show any significant changes due to mining. The passage of the F22 panel exhibits no significant changes in metal concentrations, and all measurements lie within pre-mining conditions. Iron shows the most insignificance due to its variability. Pre-mining levels fluctuate between 0.14 – 1.8 mg/L. Post-mining levels remain between 0.4 – 0.85 mg/L. Aluminum levels have much less variability than iron. Manganese shows the least variability. All post-mining levels are within the natural variation of pre-mining levels.

Sulfates exhibit a relatively constant presence in the groundwater pre-mining. After the passage of the F22 panel, the sulfate levels decrease. Since sulfate levels are shown to respond to changes in groundwater level from piezometer-HS, the decrease is correlated to the increase in the groundwater level.

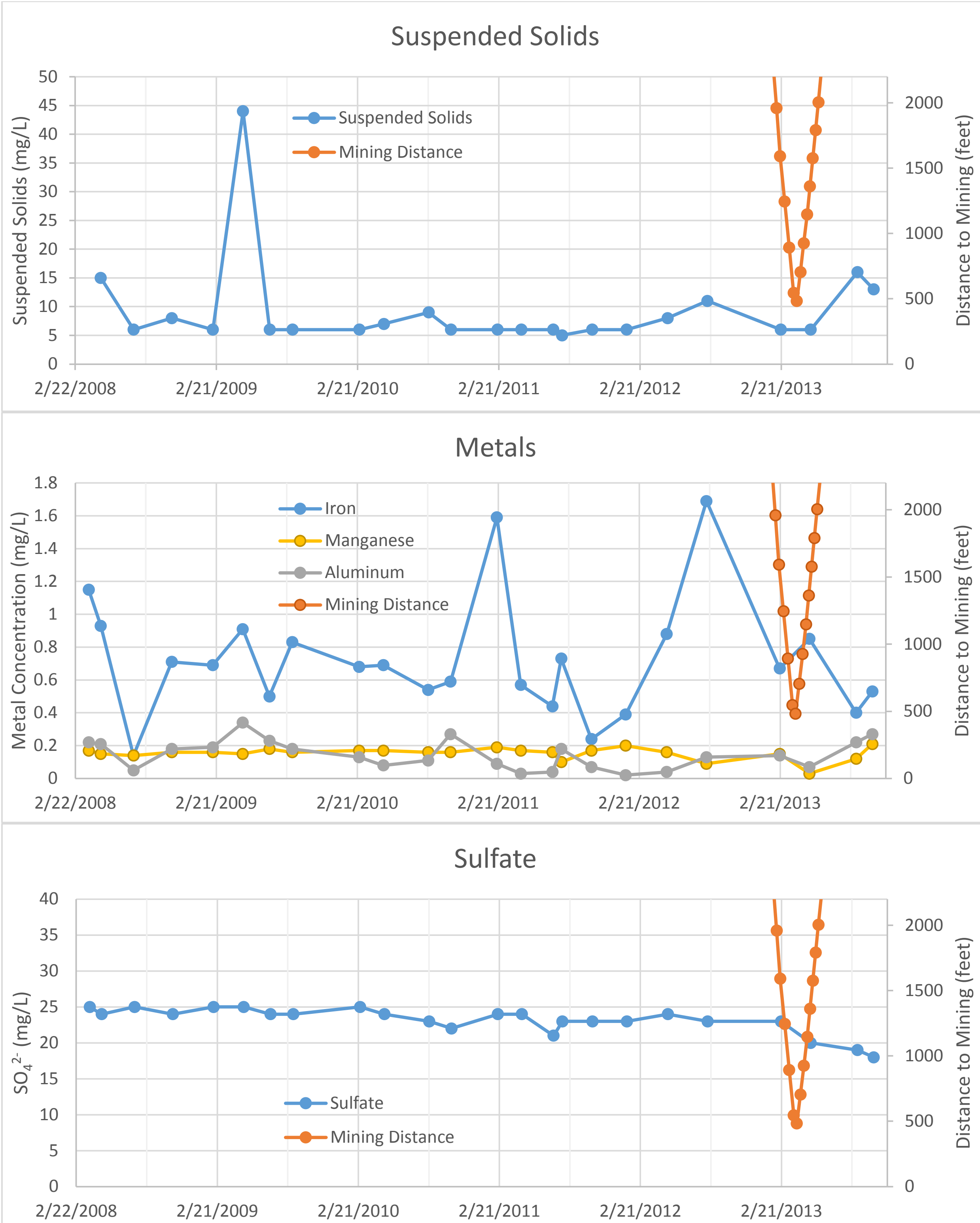


Figure 5.8: Groundwater quality measurements at piezometer-FS

Post-mining data is only available 5 months after the F22 panel is nearest to piezometer-FS. Therefore, long term trends cannot be determined. However, the recovery of suspended solids and metals is shown to occur quickly and return to pre-mining conditions. Sulfate levels are shown to follow groundwater level trends. Groundwater levels at piezometer-FS shows an increase. The increase is marginally significant so mining may or may not be contributed to the increase. A more in depth understanding can be made with the use of subsidence modelling.

5.2.4 Subsidence Modelling

Subsidence modelling is highly useful in determining the changes on the surface when subjected to longwall mining. The software utilized in this analysis is the Surface Deformation Prediction System (SDPS v6.1P), developed by Dr. Zacharias Agioutantis and Dr. Michael Karmis of Virginia Polytechnic Institute and State University (Agioutantis and Karmis 2013b). The software was chosen because it was developed from analysis in the Appalachian area. Therefore, the software results are applicable to the study region. The software also accounts for the influence of topography during subsidence, which is determined to be a highly significant factor (Agioutantis and Karmis 2013). The most useful application of the software is the computation of strains that occur due to subsidence. Stains can be related to the stress that is experienced on the surface. If the stress exceeds the strength of the soil, increased pore space, fissures, mass wasting, and compression rolls can occur. These occurrences can have significant changes of the groundwater system.

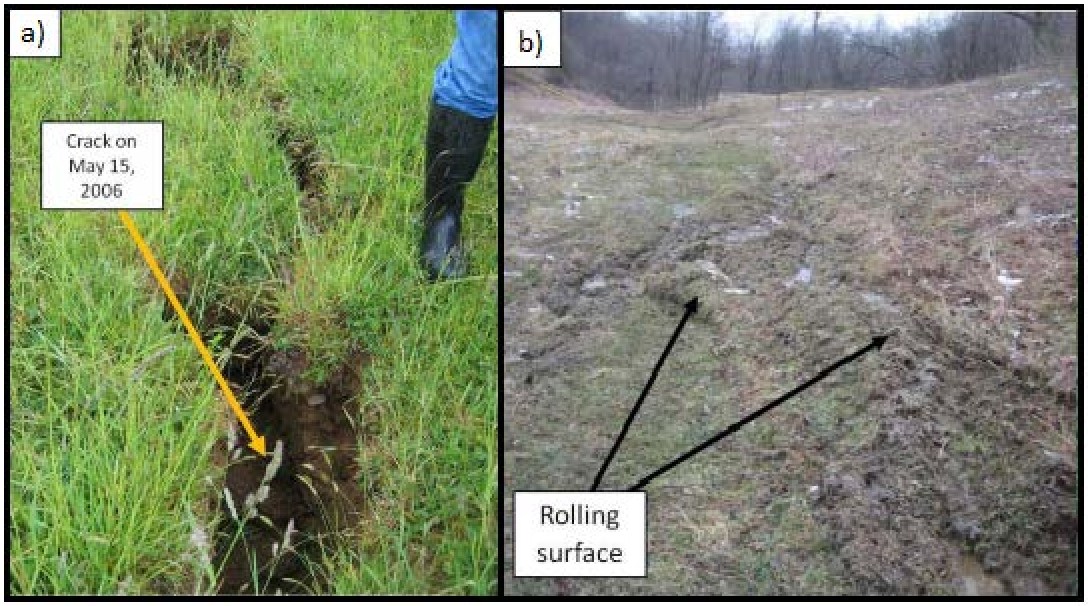


Figure 5.9: Photograph of a) fissure and b) compression rolls created by longwall mining (Iannacchione, Tonsor, et al. 2010)

Subsidence analysis is performed on both piezometers. The first is piezometer-HS. An area around piezometer-HS is chosen so that prediction points may be input into the SDPS program. Only the section of the F18 panel nearest to piezometer-HS is chosen to increase the number of prediction points in that area and also reduce computation time and space. The prediction points are used to calculate subsidence, strains, and other information at the surface. The elevations for the prediction points are obtained from the DEM's using ArcGIS and input into the program. A constant coal elevation of 600 ft is also input into the SDPS program, resulting in overburdens ranging from 500 to 800 ft. The range in overburdens illustrates why subsidence modelling that incorporates topography is critical. The F18 panel is 1,100 ft wide, and the face ends 245 ft from piezometer-HS. An extraction height of 6 ft is also input into the program.

The results for strains are calculated, and the output text file can be imported into ArcGIS for analysis. Figure 5.10 shows the location of the prediction points used in the analysis at 50 ft spacing and the calculated strains. The strains range from 5.09 to -5.48 millistrains (1 millistrain = 1 mm/m), positive referring to tensile strains and negative referring to compression strains. The piezometer is located in the zone of tensile strains. Tension zones are most critical since soil and rock have much lower tensile strengths compared to their compression strength. Using ArcGIS, the tensile strain at piezometer-HS is found to be 1.04 millistrains. This amount of strain is unlikely to cause failure in the form of open fissures, but the soil will increase pore space due to the elongation. The increase in pore space allows for greater water contact on the soil, which can lead to increases in metals, sulfates, and suspended solids as mentioned earlier.

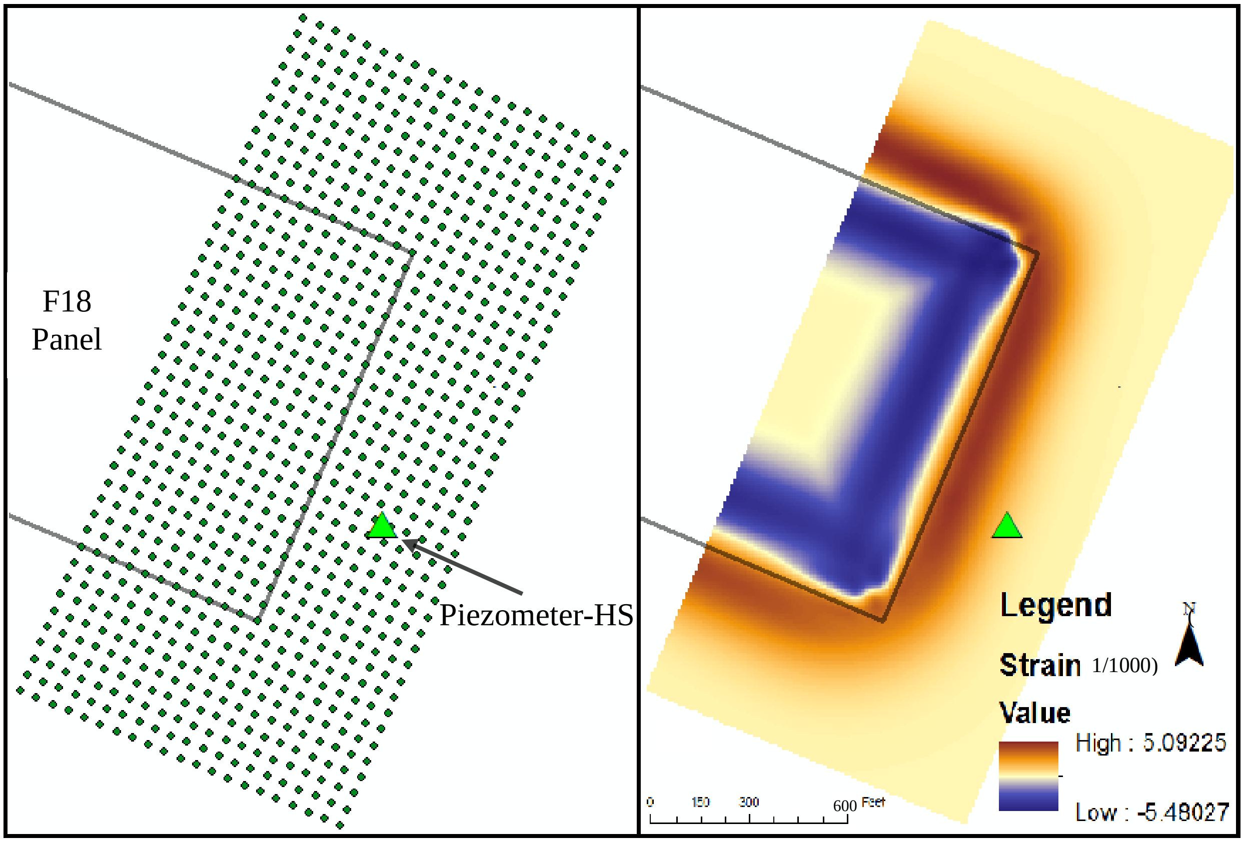


Figure 5.10: a) Prediction points for SDPS and b) calculated strains for piezometer-HS analysis

A similar analysis is performed on piezometer-FS. The panel dimensions are approximately 1,500 ft x 11,400 ft. The prediction points are spaced 100 ft apart and extend 500 ft beyond the panel dimensions. The elevations of the prediction points are extracted from the DEM and input into the SDPS. All other inputs remain the same as piezometer-HS.

The strain results are imported into ArcGIS and displayed in Figure 5.11 along with the prediction point locations. The general trend shows that compression strains are located within the panel and tensile strains are located away from the panel. The figure also demonstrates how the magnitude of the strains is related to the overburden. The darker red zones indicate areas of high tensile strains and are located at the lower elevations. Lower elevations relates to lower overburdens. Lower elevations are also where major streams are located. Strains in these areas are calculated to exceed 5 millistrains. Depending on the bedrock and bed load in the stream, stresses can exceed the strength of the rock where fractures can open within the stream, causing subterranean flow of water. The strain measured at piezometer-FS is 0.0715 millistrains. This amount of strain results in negligible effects to the ground surface.

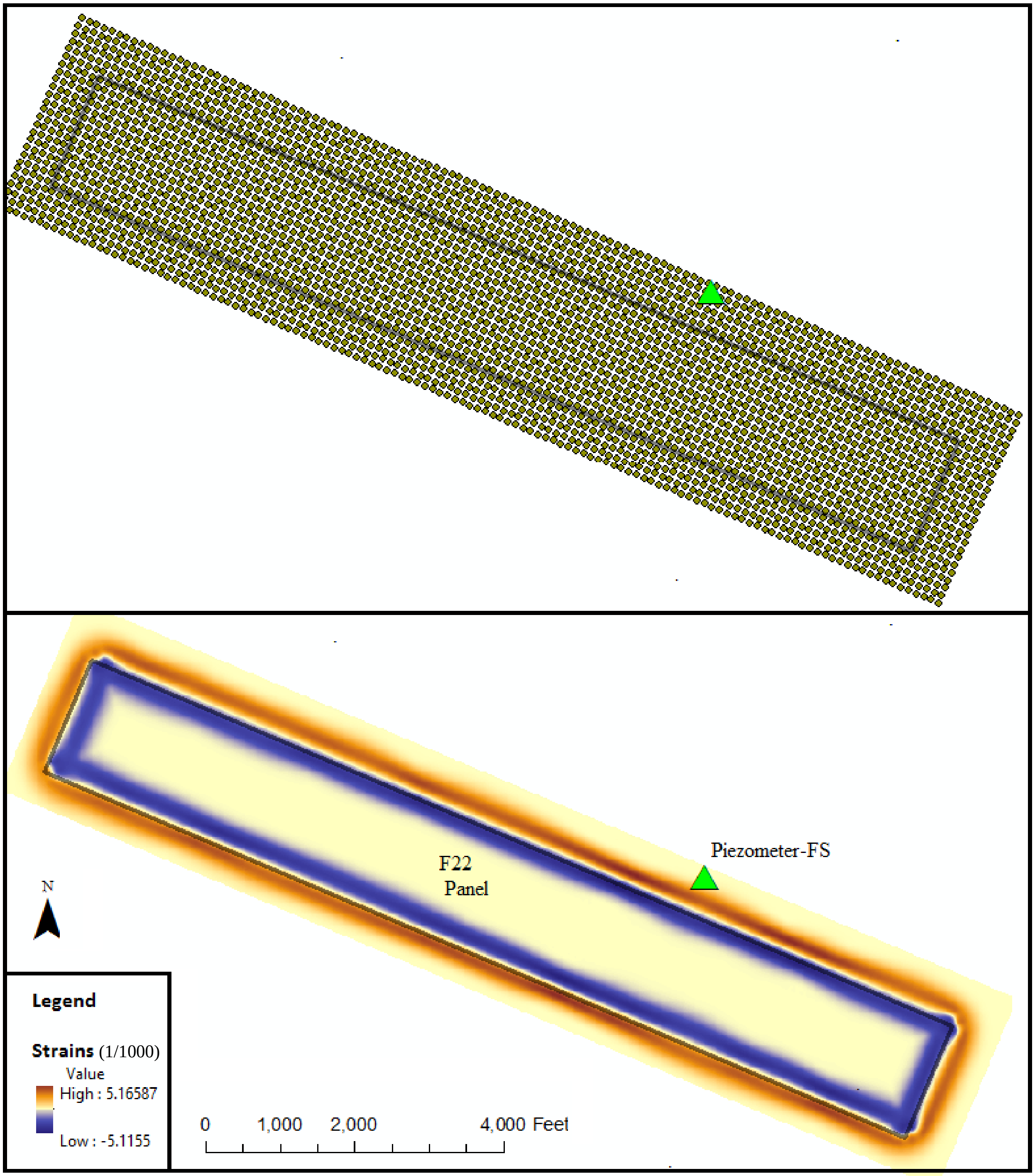


Figure 5.11: a) Prediction points for SDPS and b) calculated strains for piezometer-FS analysis

Groundwater and subsidence analysis was performed on all 9 piezometers. Piezometer-HS and piezometer-FS were chosen for discussion since they represent different cases of how groundwater can be affected. Table 5.4 represents a summary of data for each piezometer. Piezometer-CS and piezometer-ES have not been undermined during this period. Piezometer-JS has been undermined during a previous Act 54 period. Piezometer-FS, piezometer-KS, and piezometer-LS experience increases in groundwater after mining when compared with pre-mining groundwater levels. All piezometers that show effects experience strain greater than 1.03 millistrain except for piezometer-KS. However, piezometer-KS is located at the beginning of a longwall panel. Subsidence near the beginning of a longwall panel is different than the other sections of the panel because the rock is still intact until the initial break (Jeran and Adamek 1991). To account for this, the geometry of the panel is changed in the longitudinal direction to where no subsidence at the beginning of the panel is equal to no subsidence at the end of the panel. The estimated distance is approximately 200 ft. New strains are calculated at 0.876 milistrains. Therefore, all effected piezometers experience strain of 1.03 or greater.

Table 5.4: Summary of piezometer analysis for Enlow Fork mine

Peizometer	Strain (1/1000)	Distance to Mining, ft	Overburden, ft	Time at Nearest Mining	Significant Negative Impact					
					Water Level	Suspended Solids	Iron	Aluminum	Manganese	Sulfates
AS	1.488	181	480	6/2012	Yes	Yes	Yes	Yes	No	No
	0.159	4		6/2013	Yes	Yes	Yes	Yes	No	No
CS	0	3,126	430	7/2013	No	No	No	No	No	No
ES	0	4,199	520	4/2013	No	No	No	No	No	No
FS	0.106	483	705	4/2013	No	No	No	No	No	No
HS	1.038	225	670	1/2010	Yes	Yes	Yes	Yes	Yes	Yes
KS	4.487	160	660	10/2009	No	No	No	No	No	No
JS	0	0	855	before 8/2008	NA	NA	NA	NA	NA	NA
LS	0	1,363	660	11/2012	No	No	No	No	No	No
KS2	0	1,654	590	6/2010	NA	NA	NA	NA	NA	NA

5.2.5 Key Observations

The Enlow Fork mine provides data for observation of today's high production longwall mines. With high production longwall mining comes added stress to groundwater aquifers and water supplies. Regardless of the magnitude of impacts to water supplies, the company must provide means to establish temporary and permanent water supplies for residents. The major findings at the Enlow Fork mine include:

- Longwall Mining – surface subsidence is almost synonymous to longwall mining. Longwall mines provide a compromise between production and added stresses to groundwater aquifers. Piezometer data indicates changes in groundwater levels and subsidence analysis of strains specifies an indirect measure of stresses that occur at the surface. Different areas relative to a longwall panel will show different effects. Adverse zones include areas of high tensile strains and low overburdens.
- Groundwater Recovery – both piezometer-HS and piezometer-FS show recovery once longwall mining has passed. Suspended solids and metals have the quickest recovery period and return to pre-mining conditions. Groundwater levels show an increase after mining. However, the final groundwater level may be lower or higher than pre-mining levels, which may relate to higher or lower sulfate levels in the groundwater.
- Distance to Mining – the distance to longwall mining has an impact on how the groundwater responds. The data implies that significant impacts are noticed when the longwall panel is within a critical distance of 225 – 480 ft. Once this critical distance is reached, residual impacts are noticed, even when mining is farther than the critical distance. The critical distance can be related to the strains experienced on the surface.

Active or long-term subsidence that causes tensile strains of greater than 1.03 millistrain is likely to have noticeable impacts on shallow groundwater. A critical distance can then be computed based on analytical equations dependent on panel dimensions, overburden, mining height, and other subsidence related variables.

5.3 DORA 6

5.3.1 Background

The Dora 6 Mine is located in southern Jefferson County near the town of Hamilton, PA. The mine is in the Lower Kittanning coal seam and is mined using room-and-pillar techniques. Doverspike Bros. Coal Company is the operator of the mine from 1983 until its closing in 1999. The dip of the coal seam runs from north to south. Although the mine is not in operation during the 4th Act 54 assessment period, the information provided from the 2nd Act 54 assessment allows for investigation on why water issues occurred.

5.3.2 Reported Water Issues

During the 2nd Act 54 assessment, a total of 42 water supplies locations were mapped. Initially (2001), 32 of the water supplies were considered affected by Dora 6 due to high levels of sulfates in the waters. Sulfate levels are highly used to indicate water contamination downstream of the coal seam as mining increases sulfate creation relative to naturally occurring events. Sulfates will also stay in solution rather than precipitate out like metals. Samples of the unaffected supplies were taken between 2000 and 2003, and some were found to contain elevated levels of sulfates. In total 39 water supplies were deemed affected due to the flooding of the Dora 6 Mine by the PA DEP. The remaining 3 water supplies were not affected since they are located above the elevation of the mine pool (Cal U. 2005).

Because sulfates are a good indication of mine water at this site, a relationship between sulfate concentrations and well depth is chosen for analysis. Sulfate levels are also important to study because drinkers of sulfate rich water can develop undesirable laxative effects. A study from the U.S. Environmental Protection Agency investigate these effects at different sulfate levels. The study shows that increased sulfate levels have increased laxative effects. Increased use of high level sulfate rich water can lead to more severe heath issues, such as dehydration. Pennsylvania's standard for sulfates in drinking water is 250 mg/L. This standard is common for many states because drinking water becomes aesthetically unpleasing because of odor, taste, and color. Laxative effects are minimal at this exposure. Sulfate levels exceeding 1,000 mg/L will likely affect a drinker (EPA 1999).

Figure 5.12 represents the trend between sulfate levels and well depth. Four inferences can be made from observation. First, springs should show little effect from mine water contamination since much of the spring water occurs from shallow groundwater above the coal seam. Springs at this site experience a minute increase in sulfate levels. Springs are considered to have a depth of 1 ft for this analysis. Sulfate concentrations in the springs do not exceed the 250 mg/L standard. Second, a large increase in sulfate levels is experience around a depth of 25 ft. This depth represents a boundary where water containing high levels of sulfate is present. Third, sulfate levels decrease at depths from 25 to 100 ft. Deeper wells penetrate through more aquifers. Therefore, more water is available to dilute the sulfate rich water. Fourth, sulfate levels increase at depths from 100 to 200 ft. These wells may penetrate through a formation that contains high levels of sulfate. The Brookville and Clarion coal seams lie at approximately this horizon and contain average levels of sulfur of 3.29% and 4.33%, respectively, compared with the Lower Kittanning coal seam with an average level of sulfur of 2.25% (Stout 1919). The inflow of this water reverses the dilution effect.

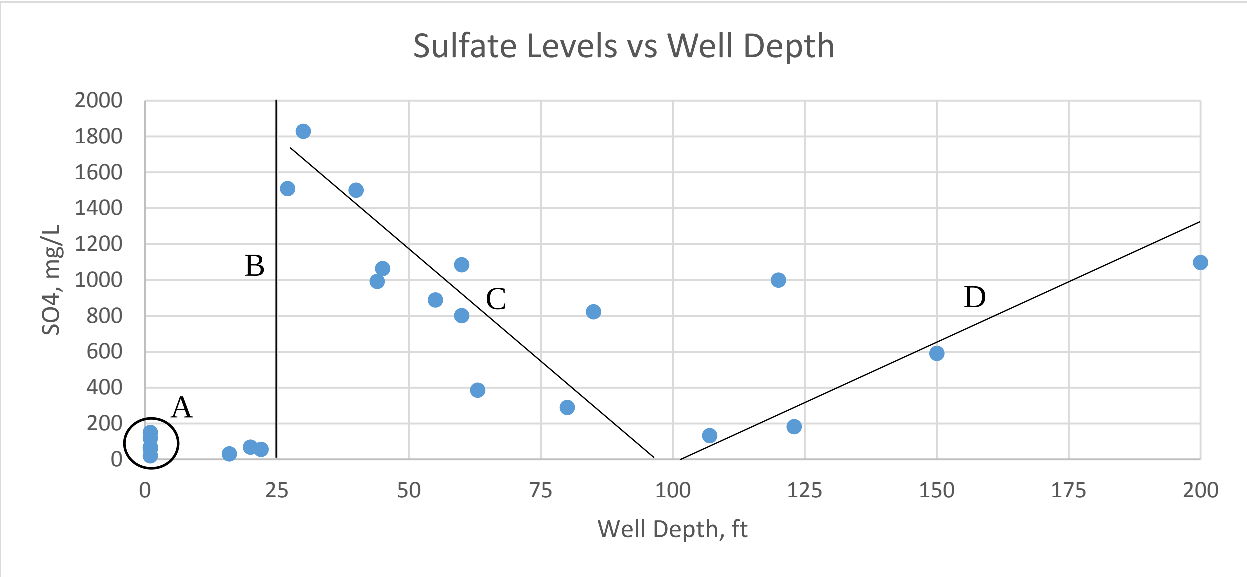


Figure 5.12: Depth of wells at Dora 6 Mine vs. sulfate levels and a) springs, b) sulfate separation zone, c) sulfate decline with depth, and d) sulfate increase with depth

The most common treatment for these water sources with high sulfate levels is installing water softeners, iron filter, and reverse osmosis (R/O) units. The water softeners and iron filters have little participation in the removal of sulfates. The R/O are efficient in removing most of the sulfate minerals. However, R/O units can only produce about 1 gallon of clean water for every 4 to 10 gallons of raw water (MDH 2013). Common practices to avoid operation and maintenance of the equipment are using bottled water, drinking only bottled water and using tap water for cooking and cleaning, using water from a spring, or hauling water to a storage tank for later use.

The solution to the Dora 6 water impacts was the company installed treatment systems for the citizens whose drinking water had been impacted. Later discussion led to the state having to pump the mine pool to an elevation of 1210’ msl and treat the water. From the visit taken with Bob Dominick, the Dora 6 mine is discharging at a rate of 350 gpm and remains at a steady elevation of 1230’ msl.

5.3.3 Groundwater Analysis

The preliminary groundwater analysis begins with the collection of essential data such as 6 month mining maps and digital elevation maps. The mine maps are then geo-referenced and information such as the mine outline and coal contours are digitally extracted. Once coal contours are digitized, an overburden contour map can be created by simply taking the difference in surface and coal elevations.

With reference to Dora 6, the overburden map shows that the Lower Kittanning coal seam outcrops in the town of Hamilton. Hamilton is located in the flood plain of Mahoning Creek. The creek is classified as having a Strahler stream order of 5, meaning the creek represents the main drainage channel for several lower order streams. In general high order streams are characteristic of having flood plains, meanders, low gradients, and erosion and sedimentation. The flood plain and meanders are visually noticeable through observation of the digital elevation maps. Streams with gradients less than 2% are considered low gradient. In the area of study, Mahoning Creek has a low gradient of 0.2%. The erosion and sedimentation characteristic are important when considering the location of the coal outcrop. The determination of the coal outcrop does not take into consideration the sediments deposited in the flood plain or the erosion of the coal seam due to changes in flow of Mahoning Creek. Figure 5.13 shows the flow of Mahoning Creek at a gaging station in Punxsutawney.

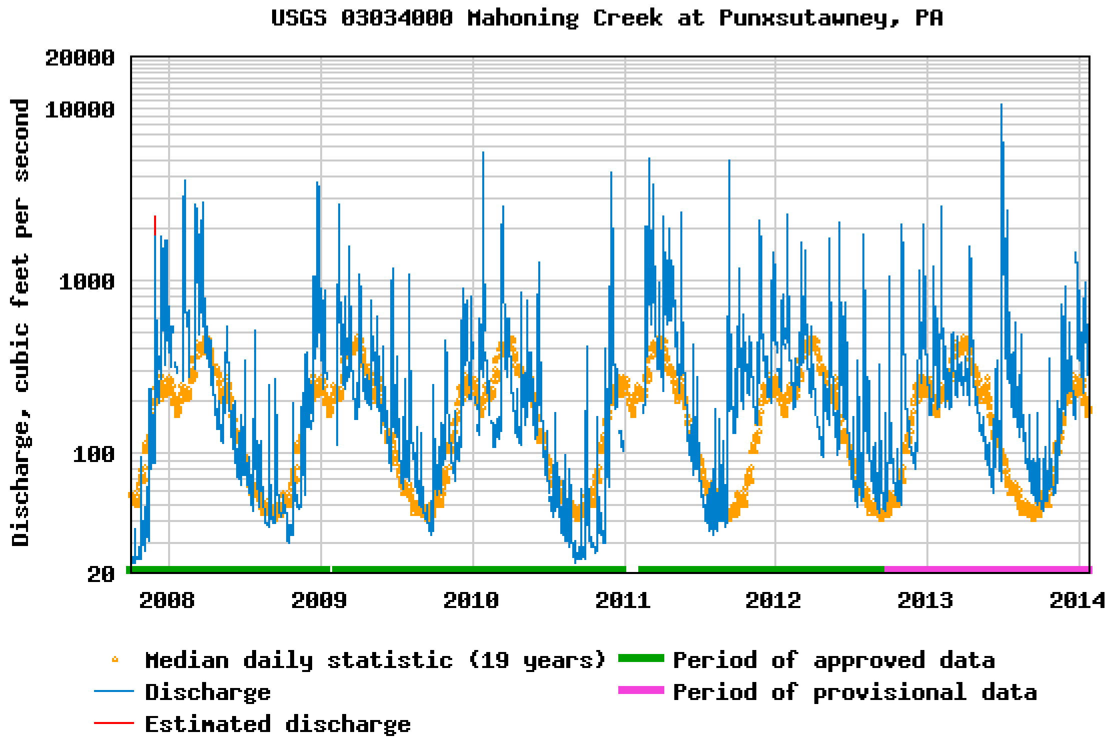


Figure 5.13: Mahoning Creek Discharge, Punxsutawney, PA (USGS 2014c)

The figure illustrates the changes in flow of Mahoning Creek since October of 2007. Seasonal variations are noticed when observing the median daily statistic. Median yearly flows range from 40 cfs in the dry season to 400 cfs in the wet season. However, peak flows can vary far from the median, especially during the wet season where flows can regularly exceed 1,000 cfs and can even surpass 10,000 cfs. Although rare extremely higher than average flows can occur such as in the summer of 2013. This high flow event is most likely the direct result of Tropical Storm Andrea, which produced rainfalls of 3 to 8 inches (Beven II 2013). The variation in flow is important for understanding erosion and sedimentation. Erosion occurs during high flow events while sedimentation occurs during low flows. This statement is valid for Mahoning Creek since flow can be related to velocity through Manning's Equation:

$$V = \frac{k}{n} R^{2/3} S^{1/2} \tag{5.1}$$

where,

- V = the cross-sectional average velocity, ft/s
- k = 1 $m^{1/3}/s$ for SI or 1.4859 $ft^{1/3}/s$ U.S. customary units
- n = the Gauckler–Manning coefficient
- R = the hydraulic radius, ft; R = A/P
- S = stream gradient
- A = cross sectional area of flow, ft^2
- P = the wetted perimeter, ft

Manning's equation is useful for determining changes in a stream's velocity and cross sectional area given a discharge quantity, Q = VA. Assuming Mahoning Creek consists of a rectangular channel where its length is much greater than the height, a relationship between flow change and the cross sectional area and the velocity is made. Figure 5.14 illustrates the relationship. Cross sectional area has a greater influence on stream flow, but velocity is directly proportional to stream flow. To increase flow by a factor of 10, the velocity will increase by a factor of 2.5 while the cross sectional area, or height since the width of the channel is constant, will increase by a factor of 4.

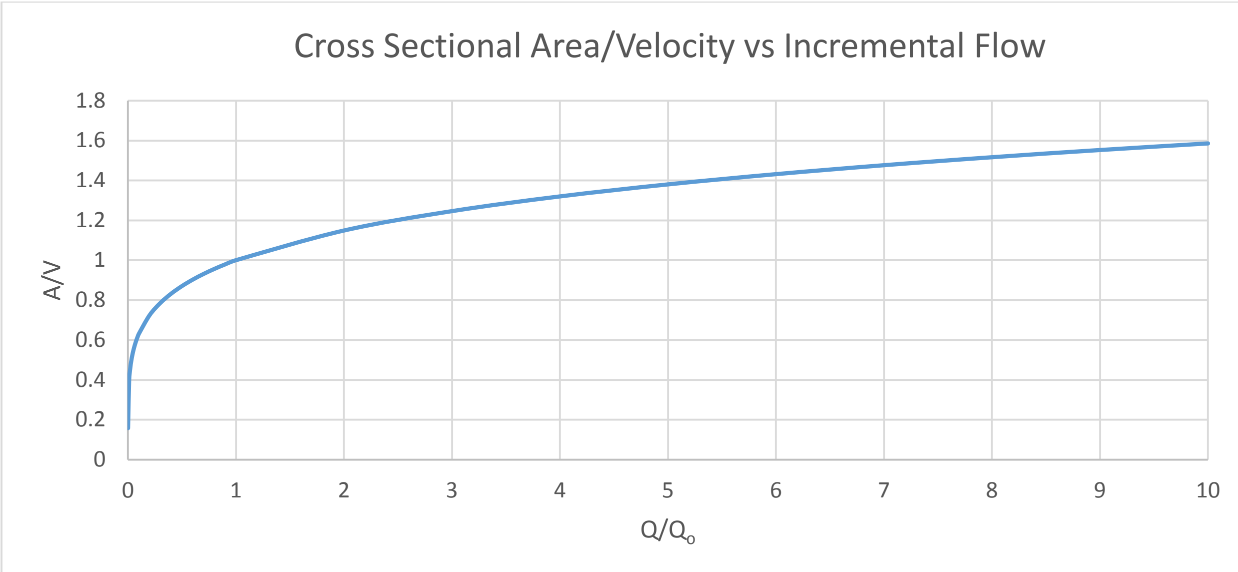


Figure 5.14: Ratio of cross-sectional area to velocity with regards to a proportional change in discharge quantity

Understanding how velocity is related to discharge in Mahoning Creek is used to determine erosion and sedimentation in the region. A valuable piece of information is relating flow velocity to erosion and sedimentation of different sized particles. Filip Hjulström, a Swedish geoscientist, proposed such a relationship in 1935. He associated particle size and stream flow with reference to erosion, sedimentation, and also transport. The graph that summarizes his research is the Hjulström diagram (Figure 5.15). The diagram is divided into the 3 discrete zones of erosion, transport, and deposition with 2 boundaries. The transport/deposition boundary is approximately log-log linear where larger particles require higher velocities to prevent settling. Smaller particles require lower velocities to prevent settling. A similar relationship is found with the erosion/transport boundary but only for particles larger than fine sands. The smaller particles require higher velocities to become eroded and remain in transport. This is because the smaller size particles consist of clays, which are cohesive since they contain electric charges. The cohesion causes the smaller particles to adhere together forming larger particles. The figure also displays the minimum and maximum flow velocities in Mahoning Creek since October of 2007. The velocities are derived using Manning's Equation. Mahoning Creek is capable of eroding pebble size particles during periods of high flow. Particles sizes classified as small boulders can be transported by the creek when introduced to the system. Deposits of particles larger than coarse sands are common. Small particle deposition will usually occur during retreat flood stages where flow velocities can decrease in large flood plains.

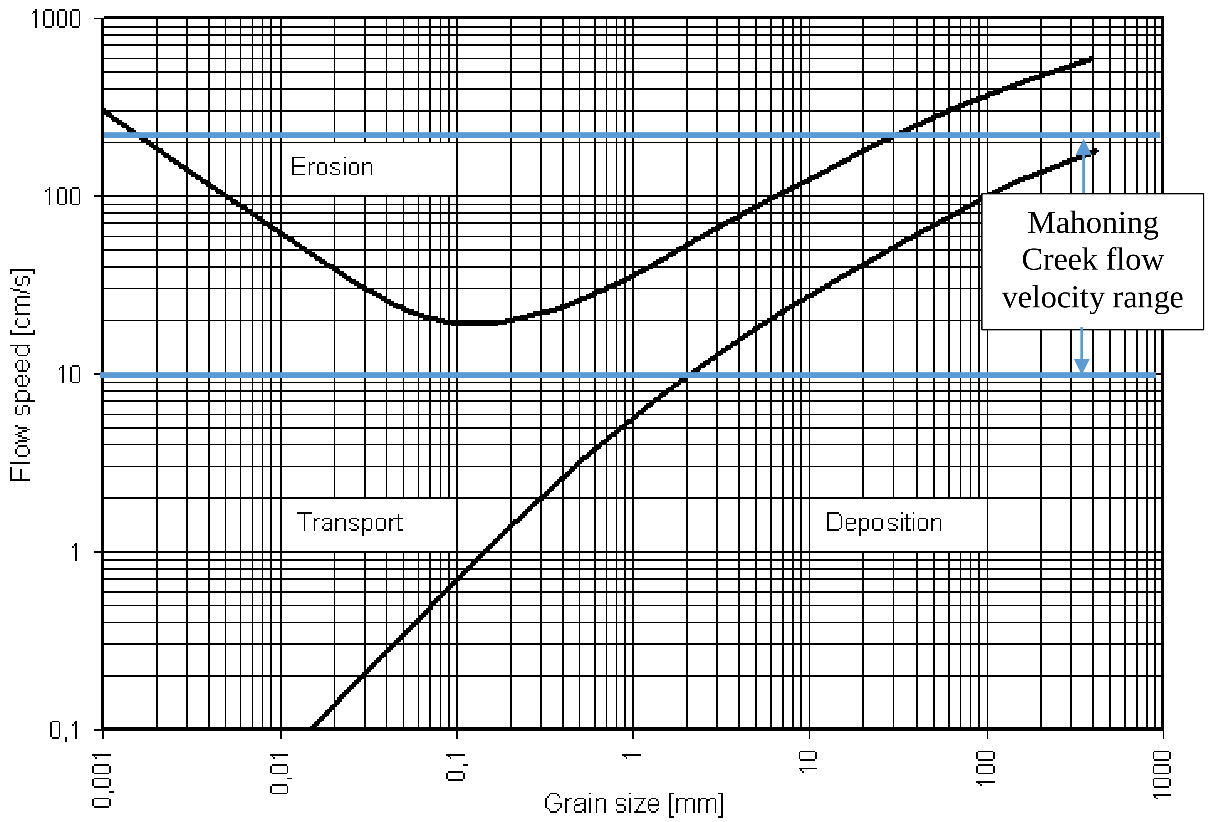


Figure 5.15: Hjulström Diagram depicting erosion and sedimentation based on particle size and flow velocity (Hjulström 1935 and Hickin 2000).

Since Hamilton is located within the Mahoning Creek flood plain, the town lies upon the sediments deposited by the creek over time. Because the size of soil particles in the town can be relatively large, the hydraulic conductivity will be higher compared to the surrounding rock. Some of the wells in Hamilton are shallow (<30 ft) and provide a sufficient supply of water to the household due to the high hydraulic conductivity of the soil.

In addition to sedimentation of soils in Hamilton, the area would also experience the erosion of soils and rock weathering, specifically to the Lower Kittanning coal seam. This erosion is why the computed outcrop is not representative of the true outcrop. The true outcrop does not represent the area where the coal seam reaches the surface but rather references the area of a coal/no coal boundary. The boundary for the Lower Kittanning coal seam in Hamilton should extend away from the valley towards the hills, but how far should it extend?

The true outcrop is best represented as the overburden contour that is equal to the depth of the soil material in the Mahoning Creek valley. Using well logs in the Hamilton area to determine soil cover, an approximate outcrop location can be determined. Soil covers in the well logs range from 8 to 39 ft. Through interpolation and judgment, the true outcrop is best represented at the 25 ft overburden contour in the Mahoning Creek floodplain. Caution is taking in the areas where the 25 ft overburden contour is located in the floodplains of Foundry Run and Perrysville Run since these streams contain less sediment. Figure 5.16 shows the difference between the computed outcrop and the true outcrop. The 25 ft overburden contour also coincides with the sulfate boundary depth for the affected water supplies. The true outcrop location can reasonably explain why shallow wells are not affected from mine water. Figure 5.17 illustrates the probable geology in the Hamilton area. The figure shows the computed coal outcrop in the area where the coal seam has been eroded by Mahoning Creek. This places the true outcrop under several feet of sediments.

The sediments restrict the flow of groundwater and, therefore, do not cause shallow groundwater to mix with the sulfate rich mine water. The lack of amalgamating describes why shallow wells less than 25 ft do not experience high sulfate levels.

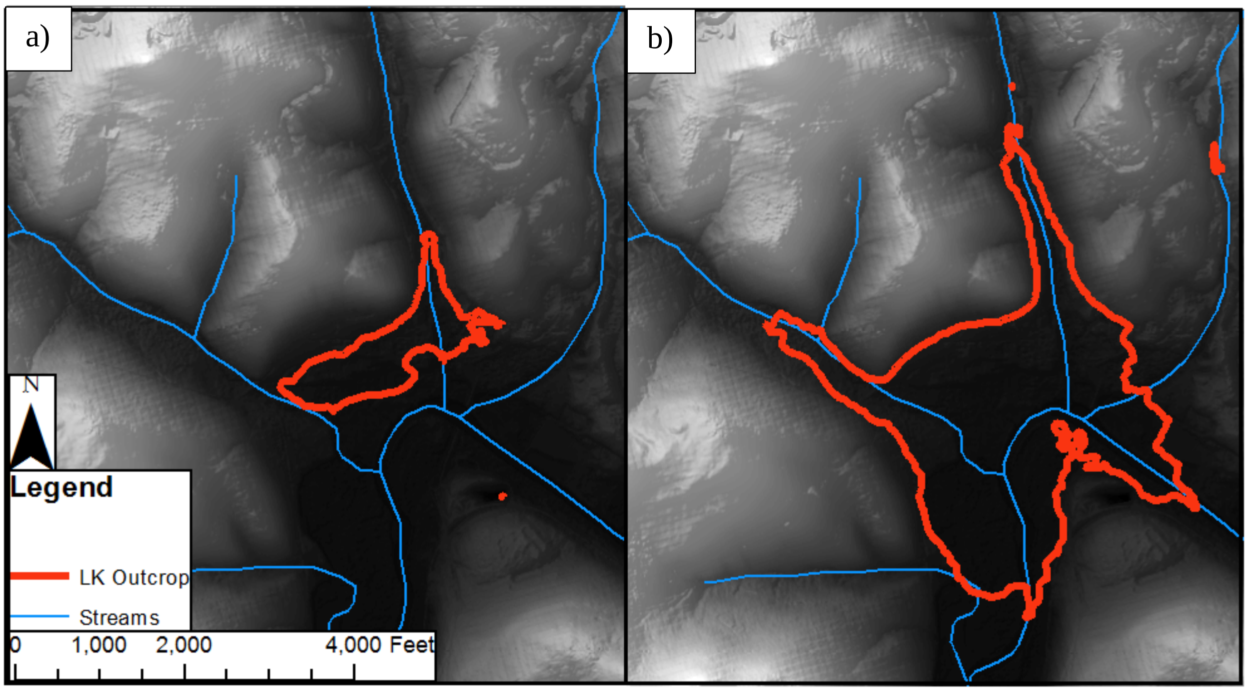


Figure 5.16: Illustration depicting a) the computed LK outcrop and b) the true outcrop

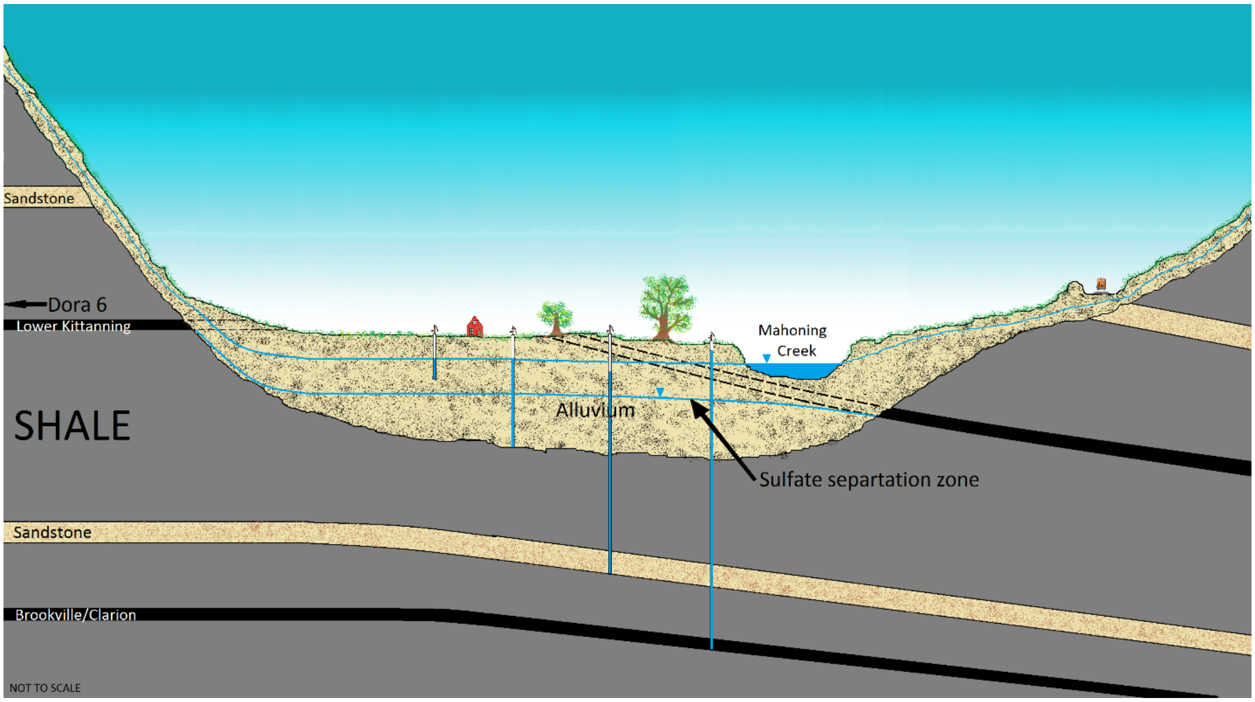


Figure 5.17: Conceptual illustration of the probable geology of Hamilton showing the alluvium relocating the LK coal outcrop and sulfate separation zone

5.3.4 Groundwater Modelling

Groundwater analysis is conducted using Groundwater Modelling Software (GMS) to determine the hydraulic properties of the Lower Kittanning coal seam that would cause mine water to move through the coal barrier and pollute groundwater in Hamilton. The GMS software used in the analysis is GMS 9.2.4, which is a MODFLOW based system. The software allows for modelling of groundwater movements based on inputs such as starting heads, constant heads, horizontal and vertical conductivities, and anisotropy. Before modelling begins, a conceptualized model is created to understand what properties should be given to the GMS model.

The conceptual model allows for a basic understanding of how the real world is represented. Figure 5.18 illustrates the model used for GMS. The model adds the basic components of the real world, such as the alluvium, shales, coal, and mine pool, so that groundwater modelling can be simplified. The model takes the local geology around the Dora 6 coal barrier as the boundary for the model. The boundary assumes that negligible influence is seen on groundwater from the Dora 6 mine beyond the extent of the boundary. Other assumptions are that the system is at steady state, the head difference remains constant, and the materials are homogeneous. The main variable to study is the hydraulic conductivity of the coal. The conductivity is a measure of how flow is restricted moving through the coal at steady state. A high value of hydraulic conductivity would not restrict flow greatly and would allow mine pool water to flow easily through coal barriers, potentially contaminating groundwater.

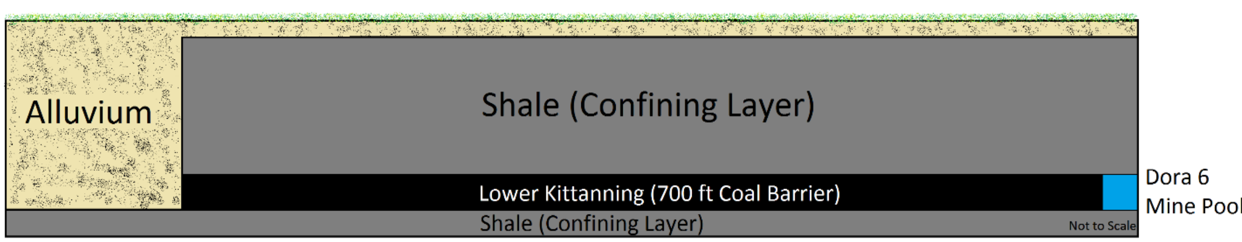


Figure 5.18: Conceptual model of Dora 6 Mine barrier for GMS model

GMS allows the conceptual model to be divided into a grid, giving similar properties to grid cells that lie within a similar material. GMS also allows for refinement of cells so that areas of interest can be analyzed in greater detail. Initial cells sizes are 10 ft in the horizontal direction and 2 ft in the vertical direction. Properties assigned to the cells that relate to the materials in Figure 5.18 are summarized in Table 5.5. These properties are chosen based on literature from several sources (Gulliver et. al 2010). Known information also useful in the model is the time mine water travelled through the barrier and the location and flow rate of a discharge on the surface. The time is approximately 2 years based on when the mine pool reached its highest point at 1260' MSL and when high levels of sulfates were measured in residents' groundwater wells. The elevation of the discharge is nearly 1190' MSL and located at the edge of the flood plain where the intact rock layers and the alluvium meet. The discharge is measured at approximately 1 gpm. Finally, boundary conditions are added to complete the model. Boundary conditions include no flow boundaries around the outside of the model and general head boundaries at the mine pool and discharge location.

Table 5.5: Initial input properties for materials in GMS model

	Horizontal Conductivity (ft/d)	Vertical Conductivity (ft/d)	Porosity (%)	Reference
Alluvium	0.5	0.5	30	Clapp and Hornberger (1978). Rawls et. al (1998) Saxton and Rawls (2006) Gulliver et. al (2010)
Coal	1.0	1.0	0.05	Qiu and Luo (2013). Mignogna (2014)
Shale	10^{-3}	10^{-5}	0.05	Esterhuizen and Karacan (2005). Qiu and Luo (2013).

Once the model is run, the use of MODPATH can be used. MODPATH allows for particles to be placed in the groundwater model so that the path and time can be measured. A particle is placed at the mine pool and is observed to move through the coal barrier. The time the particle reaches the end of the barrier is computed and observed. Changes to the hydraulic conductivity value of coal is altered until the desired time is reached. The final value calculated for the hydraulic conductivity of the coal is 0.57 ft/d, well within the range of researched values (1.12×10^{-4} – 14 ft/d). This value represents the conductivity for the entire coal barrier. Studies have shown that areas of coal with low overburdens have lower values of conductivity than areas with high overburdens. This corresponds to conductivities in the barrier being higher are the discharge location and lower near the mine pool. The average conductivity also falls above average for researched values of coal hydraulic conductivity. Above average conductivity can explain why the barrier length is insufficient at reduced the flow of water from the mine pool towards shallow groundwater.

A second GMS analysis is done assuming fractures contribute to the discharge. Fractures usually occur near the surface where the rock has undergone extensive physical and chemical weathering. Fractures are also assumed to be related since the discharge occurs at a single location. Within the model a fracture is placed at the interface of the alluvium and the solid rock layers. The fracture is made by decreasing the cell dimension and increasing the conductivity. A fracture aperture of 0.1 in. and a fracture length of 20 ft are assumed. The aperture represents the opening of the fracture at the rock/alluvium interface and the length is the depth to coal. Since creating a 0.1 in. cell in GMS would be cumbersome and require more computation, a cell 0.1 ft in width is made, and an equivalent hydraulic conductivity of 18.0 ft/d is given to those cells (Langevin 2003). The final model with the calculated head values and flow path of the mine water is shown in Figure 5.19.

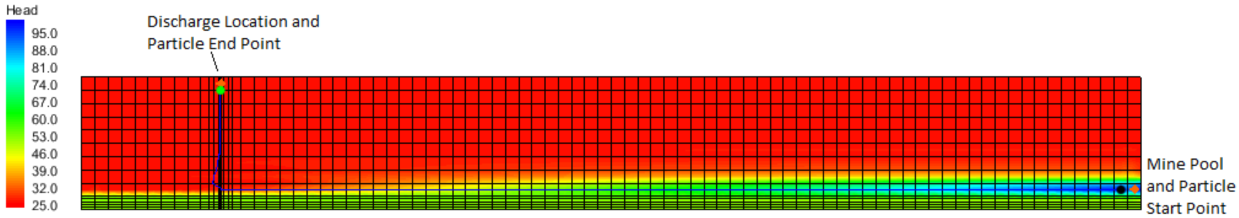


Figure 5.19: GMS computed head values and particle path for Dora 6 Mine barrier

The model shows how most of the head loss takes place through the coal seam. There is approximately a 43 ft head loss over the length of the barrier until the fracture is reached. The remaining head is lost through the fracture and also the elevation change to discharge at the surface. A comparison of the calculated head and the modelled head at the discharge point, 0.30 ft and 1.15 ft, respectively, can be shown to be approximately equal with all given assumptions. The model also shows an error of 0.104% for the flow budget, indicating that minimal water is being lost or gained to the model. Given that the water budget error is minimal and that final computed values compare with calculated values using Romm fracture flow theory (Romm 1966), the model is a good representation of event that occurred at the Dora 6 mine.

5.3.5 Key Observations

Dora 6 is an example of how a mine can have impacts on water resource quality after closure. The 2nd Act 54 report states that the Dora 6 Mine would not be permitted to mine under 2003 regulations. Regulations help reduce the risk of a similar incident from occurring, but every mine should be considered individually for exclusive features. The unique factors found at the Dora 6 Mine include:

- Structural Dip – the slope of the Lower Kittanning coal seam is oriented north to south. The town of Hamilton is located on the down-dip side of the mine. Although a coal barrier of approximately 700 ft was left in place to prevent surface flow of large quantities of water from the mine, today's knowledge and standards would not approve the permit under Dora 6's conditions.
- Mine Pool Elevation – upon closure of the mine, Dora 6 was not intended to have a controlled mine pool. The maximum elevation of the pool is 1260' MSL before discharging from the shaft on the surface. This represents a difference of over 70 ft of head in Hamilton. The coal barrier is under-designed in restricting flow of mine water under these head conditions.
- Erosion and Sedimentation – Mahoning Creek plays an integral role of the geology in Hamilton. The town sits on the flood plain of Mahoning Creek, allowing for erosion of the coal seam and sediment deposits of over 30 ft. This process relocates the coal outcrop. The true outcrop now becomes located under several feet of sediments, rather than expressed on the surface. The absence of an expressed surface coal outcrop does not necessarily imply the coal seam is continuous. Areas where streams exhibit high amounts of erosion and sedimentation within close proximity to coal seams are the most likely candidates for washing away of coal seams.
- Water Quality – pre-, active, and post-mining water quality samples of wells and springs should be taken. Samples should also be taken of the mine pool water. Comparisons can determine whether water sources have been altered due to mining or natural causes. Site specific values of hydraulic conductivities can help determine the dilution capability of coal barriers.

6.0 SUMMARY

The 4th Act 54 Report studies the impacts of underground coal mining to surface features in Pennsylvania from 21 August 2008 to 20 August 2013. During this period a total of 46 mines cover an area of 30,303.8 acres. The total reported impacts related to water supplies is 855 with 784 related to active mines with the assessment period. A total of 371 are resolved as the company being liable for the reported effect. Of the remaining 484, 286 are resolved as the company having no liability while 198 are unresolved.

Data is utilized from the BUMIS database to tally the effects associated with underground coal mining. The data is compared with previous reports to study trends through time. Case studies are also utilizes to examine trends within individual mine sites. The following trends are gathered through analysis of the data:

- Seasonal Variation – Most water supply effects are reported during the dry season and few in the wet season. The pattern follows that of natural fluctuations in groundwater and precipitation. Most effects that are resolved as not due to mining within a mined area are generally related to dry conditions. Seasonal variations are also seen for company liable effects, indicating that mining may exacerbate natural effects.
- Mined Area – Under current conditions, occurrences of water supply effects show no strong correlation to mined area. A general positive trend is seen between mined area

and occurrences of water supply effects, but other factors, such as seasonal variation, show greater influence.

- Groundwater Recovery – Piezometers that experienced significant drops in groundwater levels also experienced full or partial recovery. The recovery period depends on certain factors such as type of mining, overburden, and when mining last occurred in the area of interest.
- Abandoned Mine Impacts – If not designed appropriately, post mining barriers between the mine pool and potable groundwater can fail causing the mine pool water to contaminate groundwater.

The observed trends aid in the determination of what factors show greatest effect on water supplies and when these factors become influential. The factors of greatest significance are overburden/interburden, proximity to mining, strain, pre-mining/post-mining data, and RPZ.

7.0 CONCLUSIONS

The purpose of this study was to analyze the relationship between water resource effects and underground coal mining, determine significant factors associated with these effects, and define when these factors become influential. The following conclusions are made based on analysis of the available data and observed trends. The significant factors are:

- Overburden/Interburden – The rock layers between a mine and an aquifer show significant influences on effects to hydrogeology. For room-and-pillar mining, aquifers greater than 200 ft over active mining experienced no significant effects. Aquifers less than 200 ft above active mining experienced increasing effects with decreasing interburden. Once mining has ceased and the mine is allowed to flood, groundwater levels in all aquifers experienced at least 90% recovery.
- Proximity to Mining – Both the geographic location of a water supply relative to a mine and the depth of the water supply are considered when analyzing the effects from mining. For room-and-pillar mining, wells that extend to the coal seam experienced significant groundwater drops up to 1,100 ft away from mining. Groundwater drops are seen to decrease as interburden increases.
- Strain – Strain is used as a mechanism for understanding the effects on groundwater due to subsidence. When calculating ground strains, overburden and distance to mining is accounted. This makes strain a useful metric for studying water resource effects since it

relates the two previous factors. For longwall mining, significant effects are noticed for piezometers experiencing strains greater than 1.03 millistrains. Strains lower than 1.03 millistrains can effect groundwater after a water source has already been affected. For all observed longwall piezometers in this study, partial to full recovery of groundwater levels is detected.

- Pre-mining/Post-mining Data - Comparable data is important to obtain when examining the condition of a water supply before and after mining. This data is used to determine what effects are due to mining or natural occurrences. Lack of data can be a deciding factor on whether a water supply has been impacted or not. Pre-mining data is useful for predicting post-mining pool elevations while post-mining water quality data is useful for determining if groundwater has been impacted by mining or not.
- RPZ – The use of RPZ for determining company liability is shown to be an inaccurate tool. Both room-and-pillar and longwall mining utilize the RPZ. However, both mining methods utilize different techniques and, therefore, should use different metrics for determining company liability. The factors of overburden/interburden and proximity to mining are best used for room-and-pillar mining methods while strain is best utilized for longwall mining. Considering all mines, approximately 20% of all undermined water supplies were reported as affected. Of the affected water supplies, only 56% are found to be company liable. This implies that only 11% of undermined water supplies were impacted by mining. The low proportion indicates that other factors are influencing the impacts to water supplies.

The factors provide useful information for predicting future impacts to water supplies in western Pennsylvania and how impacts can be avoided or mitigated. Site specific conditions should be considered that may influence these factors such as faults within the overburden rock or large scale earth moving operations such as surface mining that can alter groundwater conditions. It is paramount to understand the local conditions at a mine in order to recognize the potential water resource effects that can arise.

8.0 RECOMMENDATIONS

For studies pertaining to a similar nature as this one, 3 major recommendations are suggested for improved data analysis. The recommendations are:

- Denser Data Sets for Groundwater Analysis – The data collected from this analysis was submitted quarterly. Therefore, only one data point is used to represent groundwater information over a 3 month period. A denser data set would allow for seasonal trends in groundwater to be observed. It is recommended that a monthly pre-mining and post-mining groundwater measurement and sample be taken 30 months prior to mining and once the mine has closed. This allows for a sample size representative of the population when doing statistical analysis. The time periods also match groundwater recovery periods of 2 years covered in literature. Measurement density should be increased in frequency during active mining. Daily measurements readings 30 days prior and after mining has occurred under a water supply or piezometer is recommended. A denser data set would also allow for an accurate measurement of when an effect occurs in time.
- Consider Locations of Piezometers Relative to Mining – As this report has shown, vertical and horizontal distances of piezometers relative to mining can alter readings. Keeping piezometers constant with respect to the vertical or horizontal direction will help determine a better relationship. Piezometers should also be examined for areas where they will experience temporary and long term strains from subsidence.

- Control Surface Environment – Since surface mining and other earth moving activities can effect groundwater measurements, it is important to consider these conditions when taking groundwater measurements. Having a piezometer in an undisturbed, isolated area will likely reduce any noise experienced in the data.

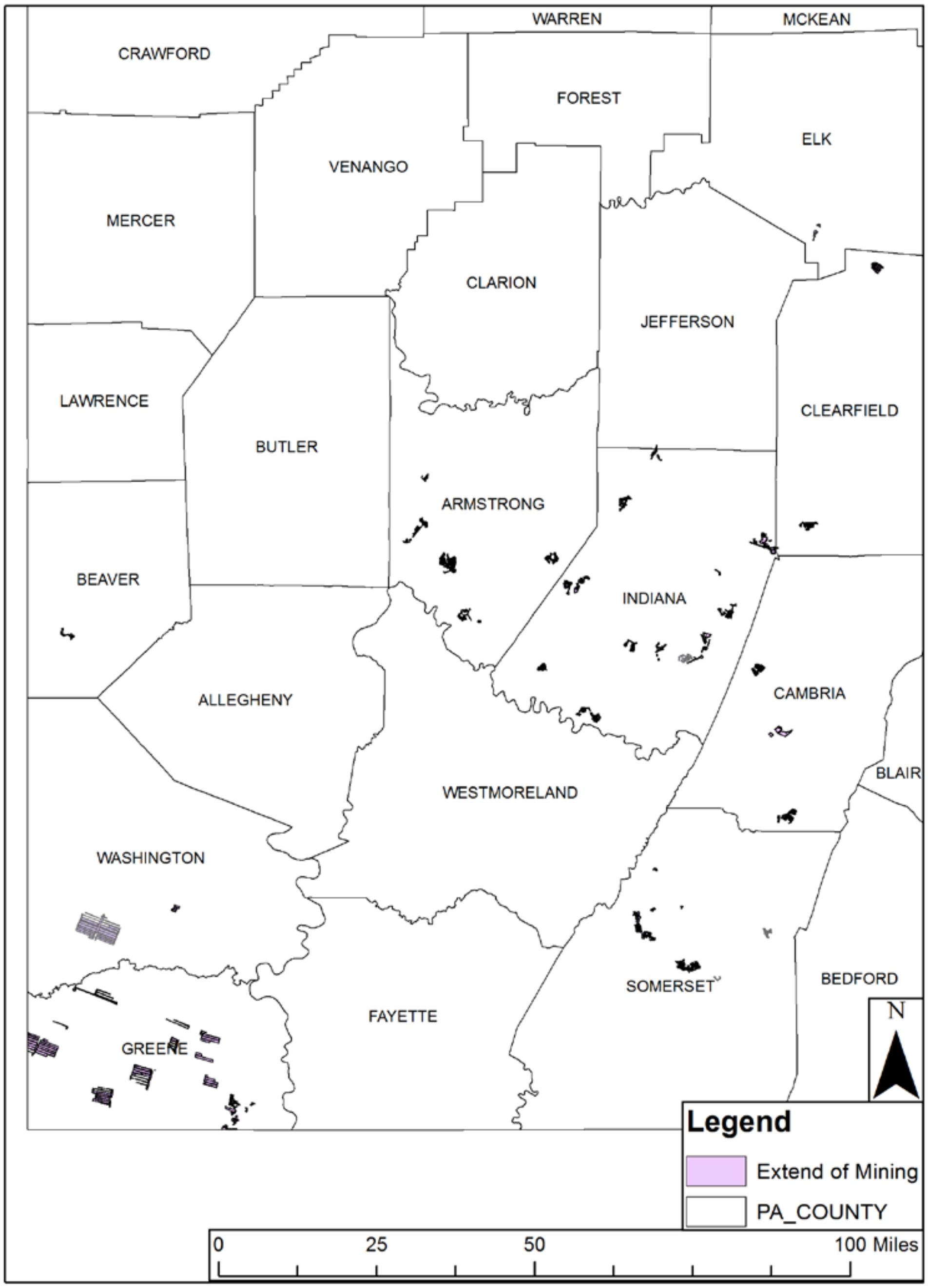
Following these recommendations will lead to fewer variables that may interfere with analysis. This results in stronger confidence in the results.

APPENDIX A

A.1 EXTENT OF MINING DURING 4^{TH} ACT 54 ASSESSMENT PERIOD

The following includes the extent of mining for all mines active during the 4^{th} Act 54 assessment period. The map includes all counties in western Pennsylvania.

EXTENT OF MINING

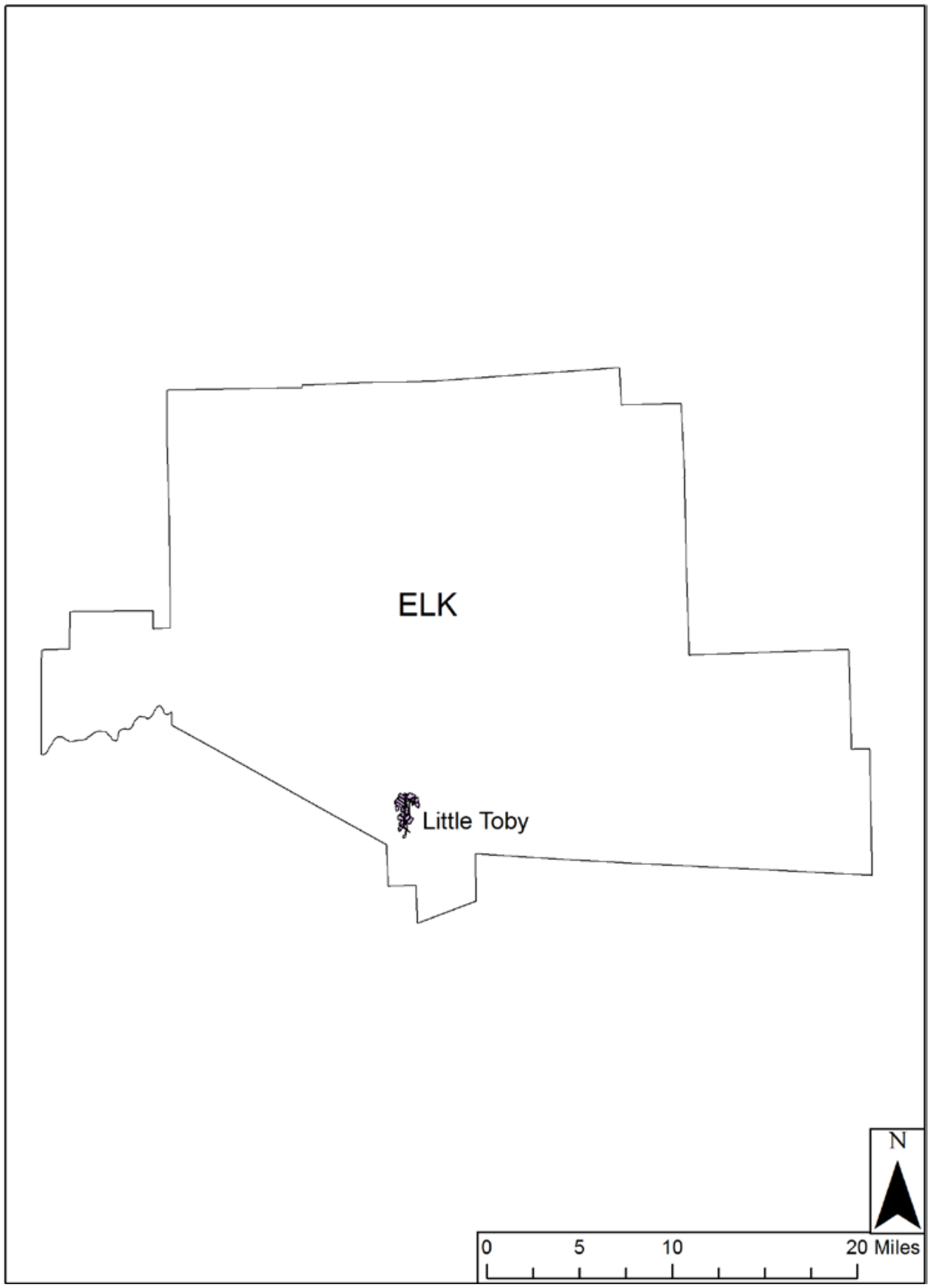


APPENDIX B

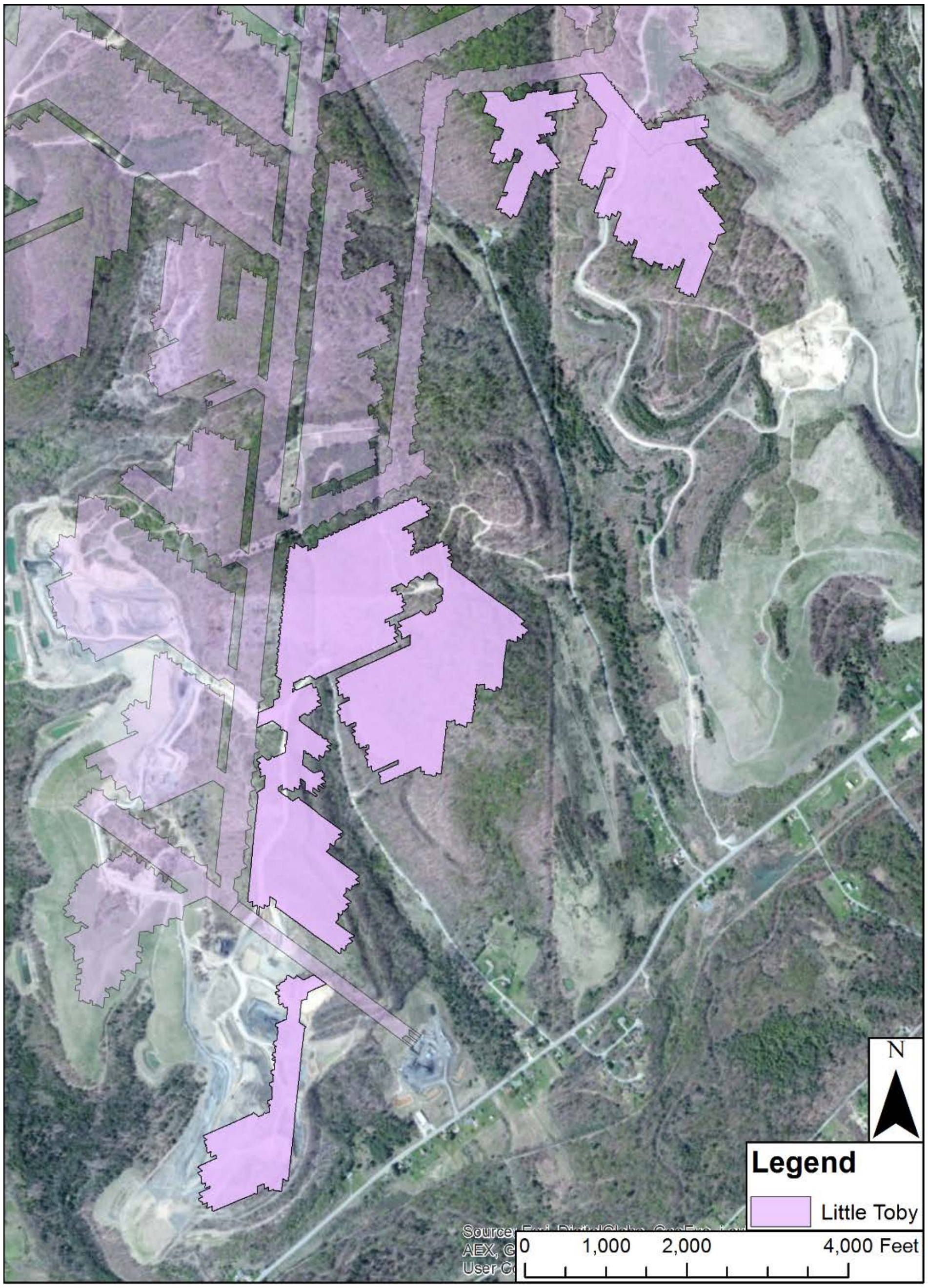
B.1 LITTLE TOBY MAPS

The following set of maps include information related to Little Toby mine. The maps include county location, satellite imagery, roads and streams, surface contours, coal contours, and overburden contours. Also are the locations of the piezometers used in the study as well as reported water supply effects. The faded areas of mining represent mining that occurred before the 4^{th} Act 54 assessment period.

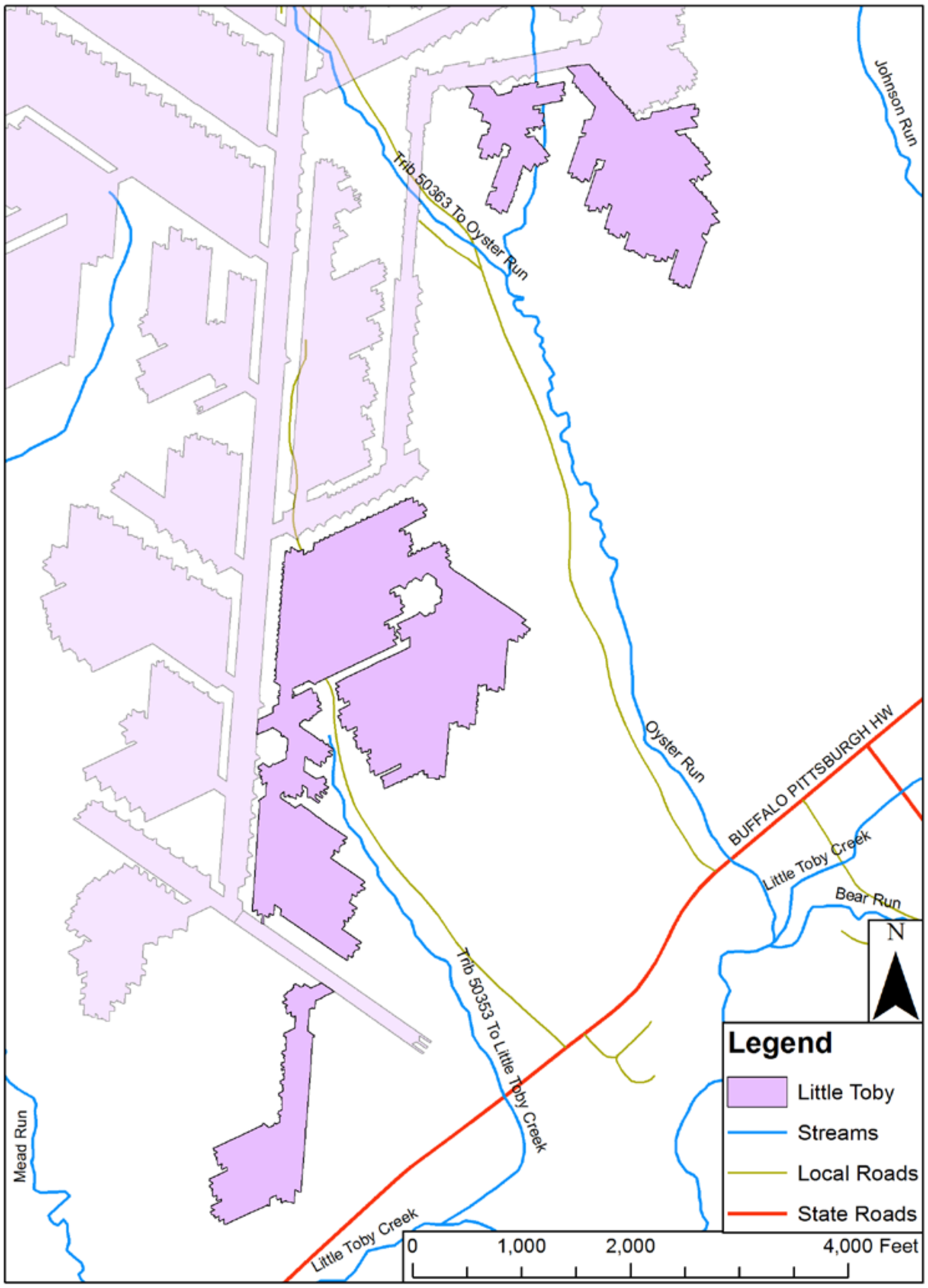
LITTLE TOBY COUNTY LOCATION



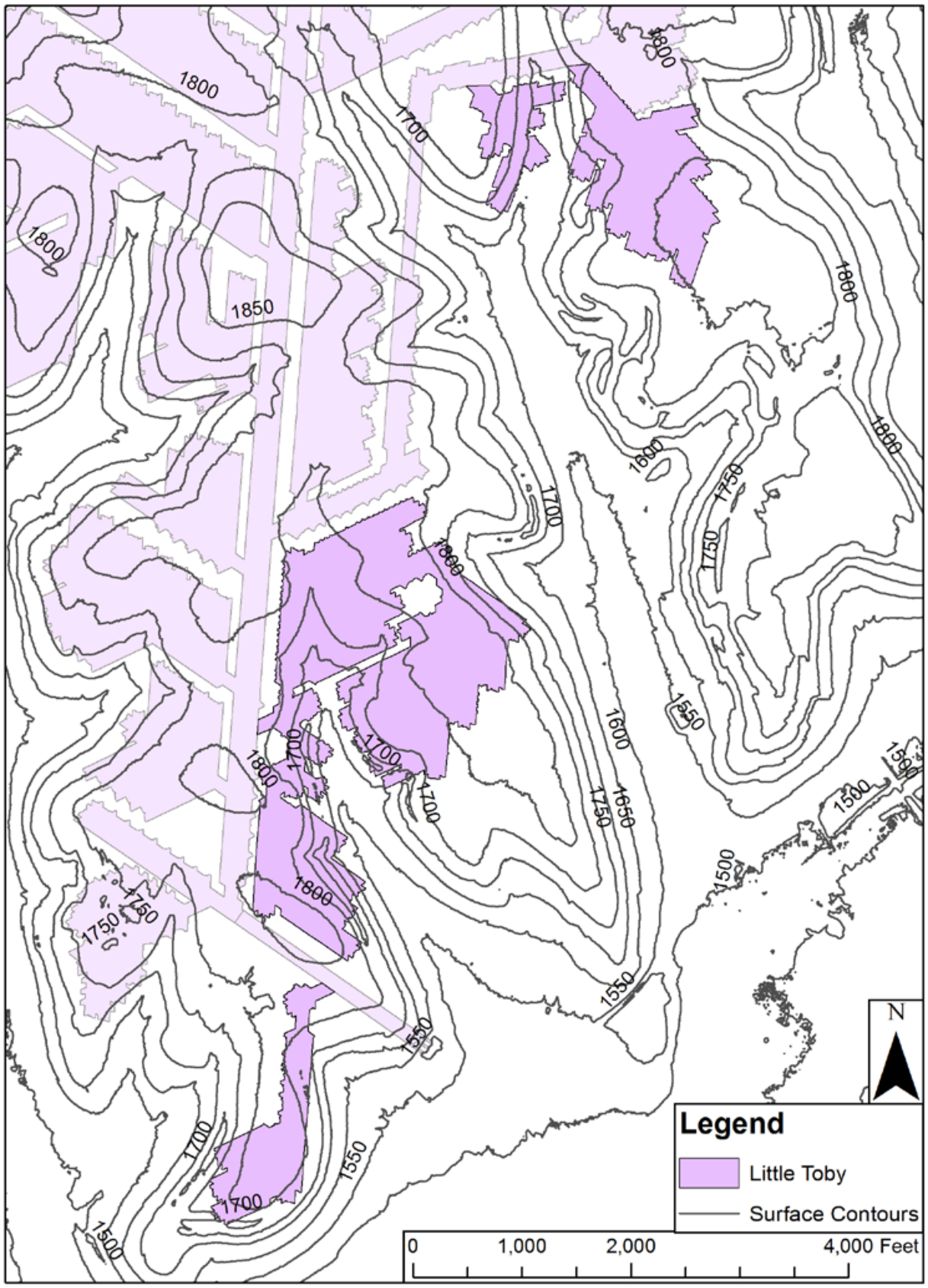
LITTLE TOBY SATELITE IMAGERY



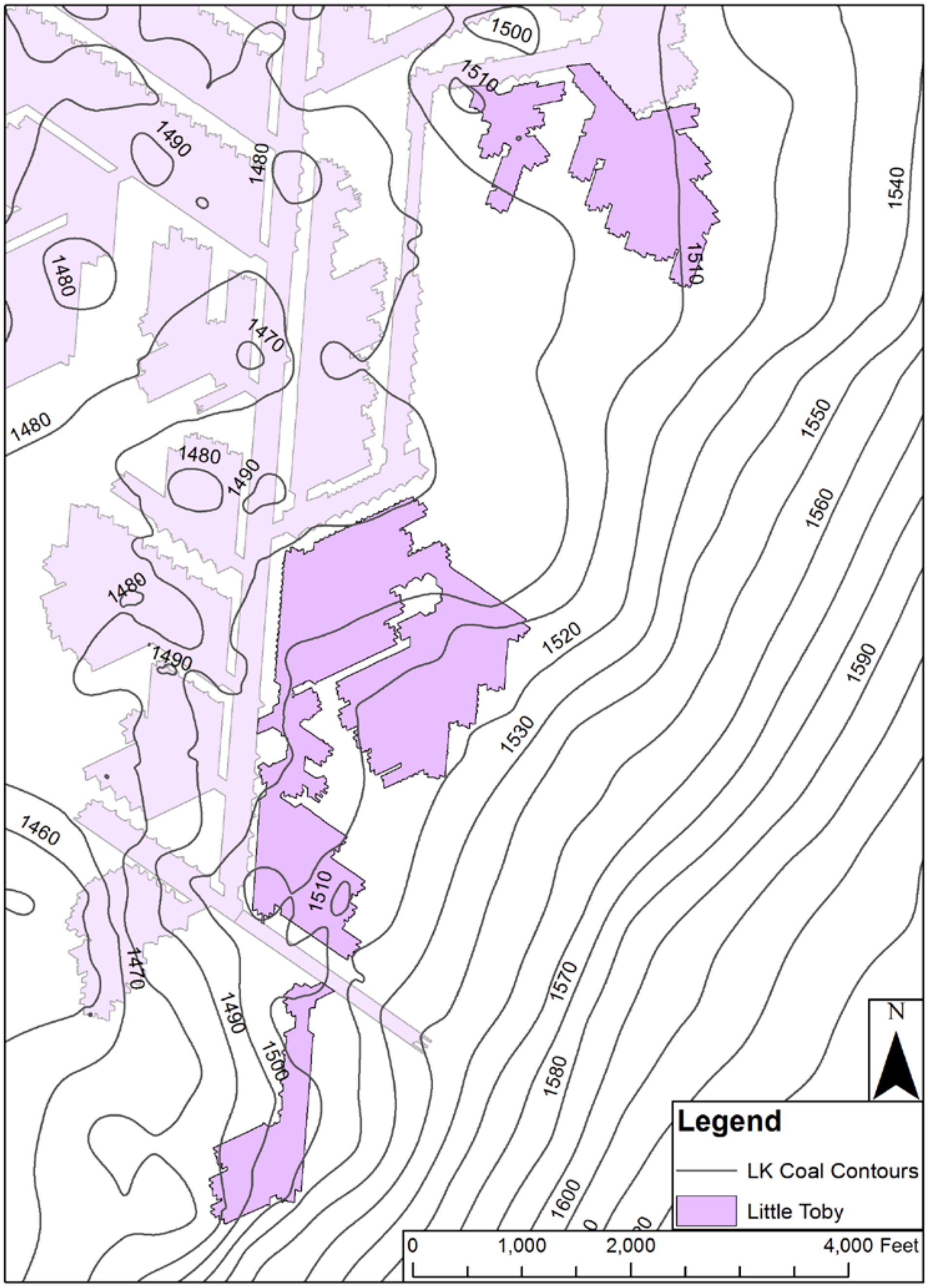
LITTLE TOBY ROADS AND STREAMS



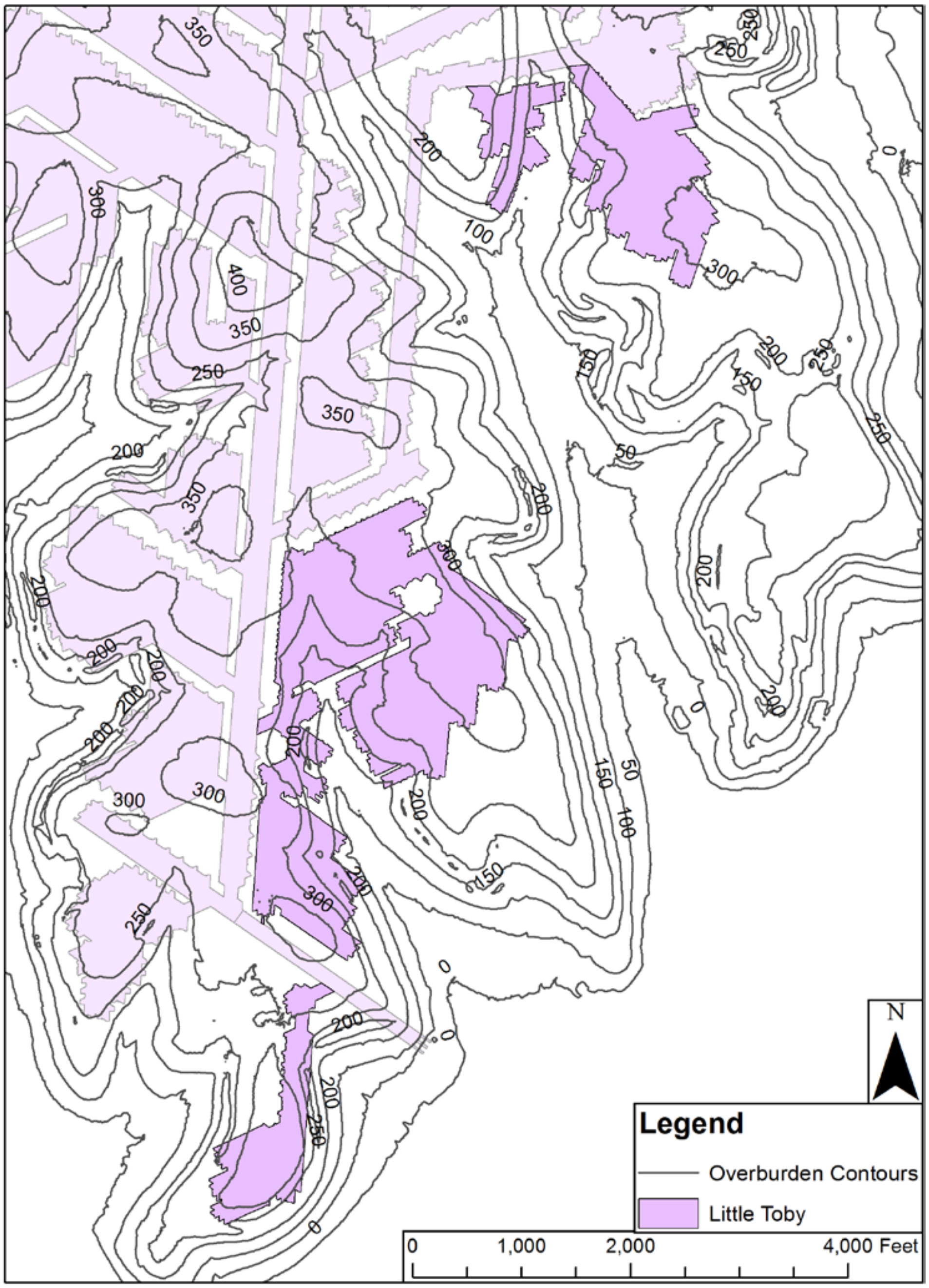
LITTLE TOBY SURFACE CONTOURS



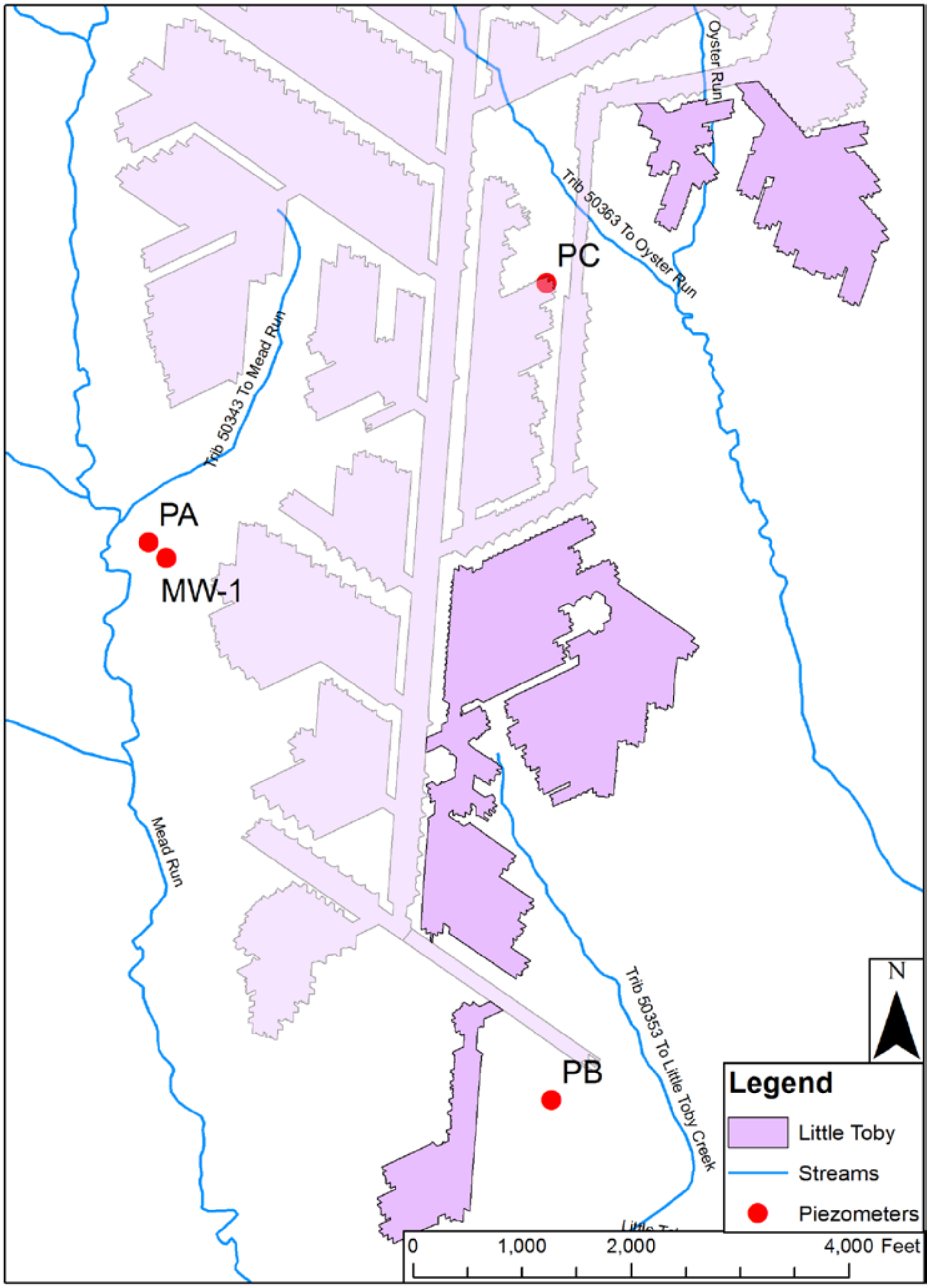
LITTLE TOBY COAL CONTOURS



LITTLE TOBY OVERBURDEN CONTOURS



LITTLE TOBY PIEZOMETER LOCATIONS



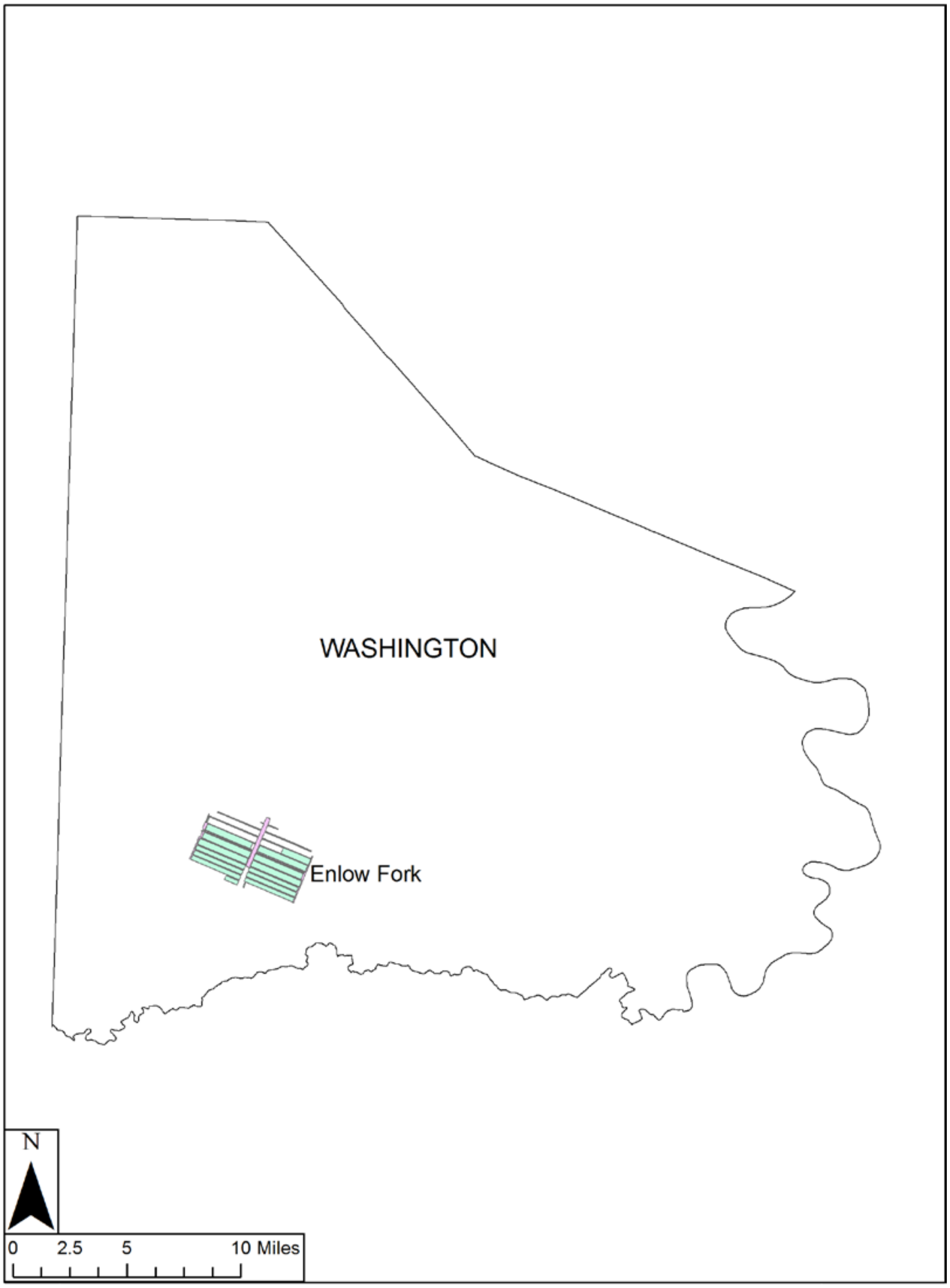
LITTLE TOBY REPORTED WATER SUPPLY EFFECTS

APPENDIX C

C.1 ENLOW FORK MAPS

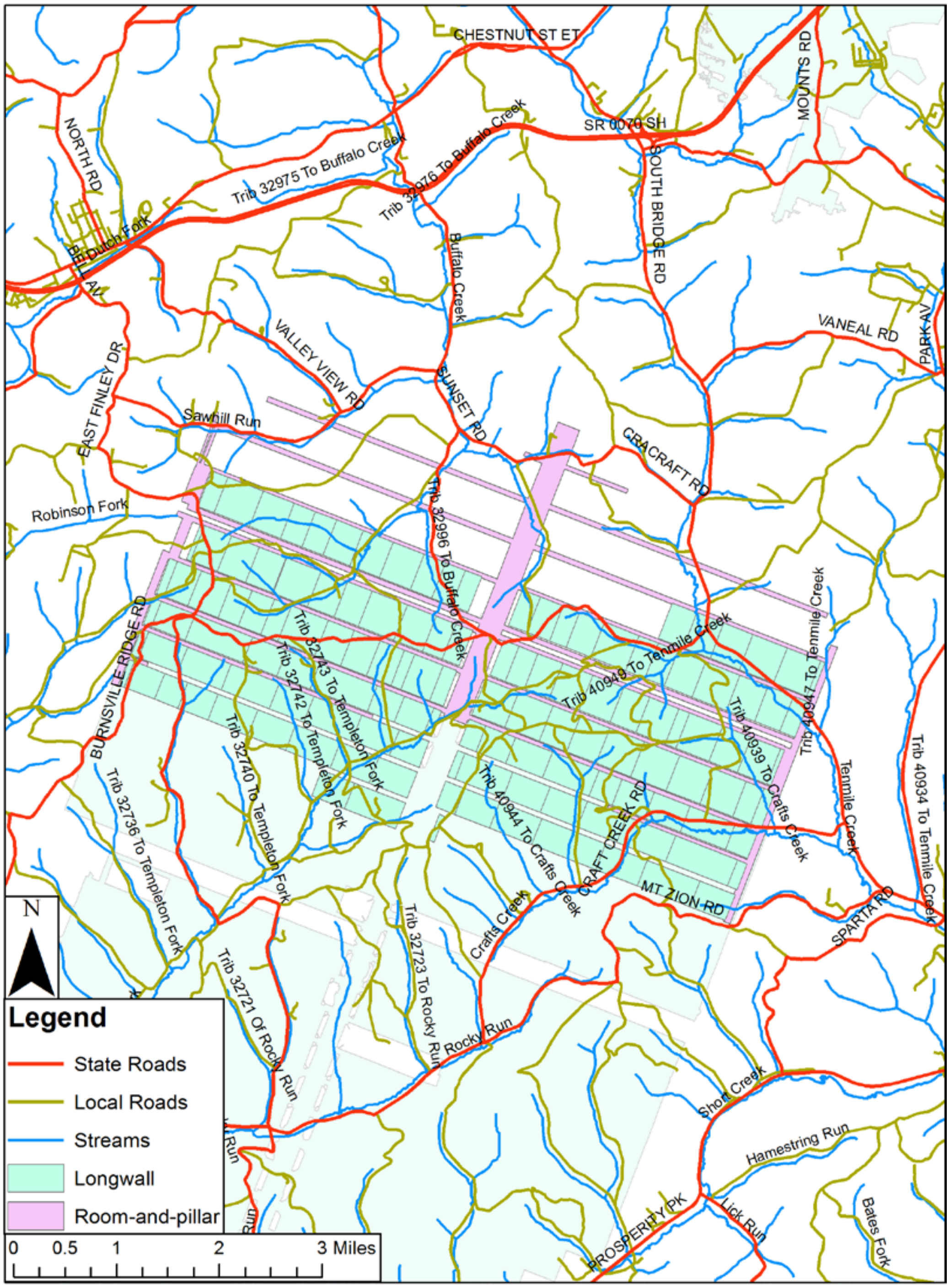
The following set of maps include information related to Enlow Fork mine. The maps include county location, satellite imagery, roads and streams, surface contours, coal contours, and overburden contours. Also are the locations of the piezometers used in the study as well as reported water supply effects. The faded areas of mining represent mining that occurred before the 4^{th} Act 54 assessment period.

ENLOW FORK COUNTY LOCATION

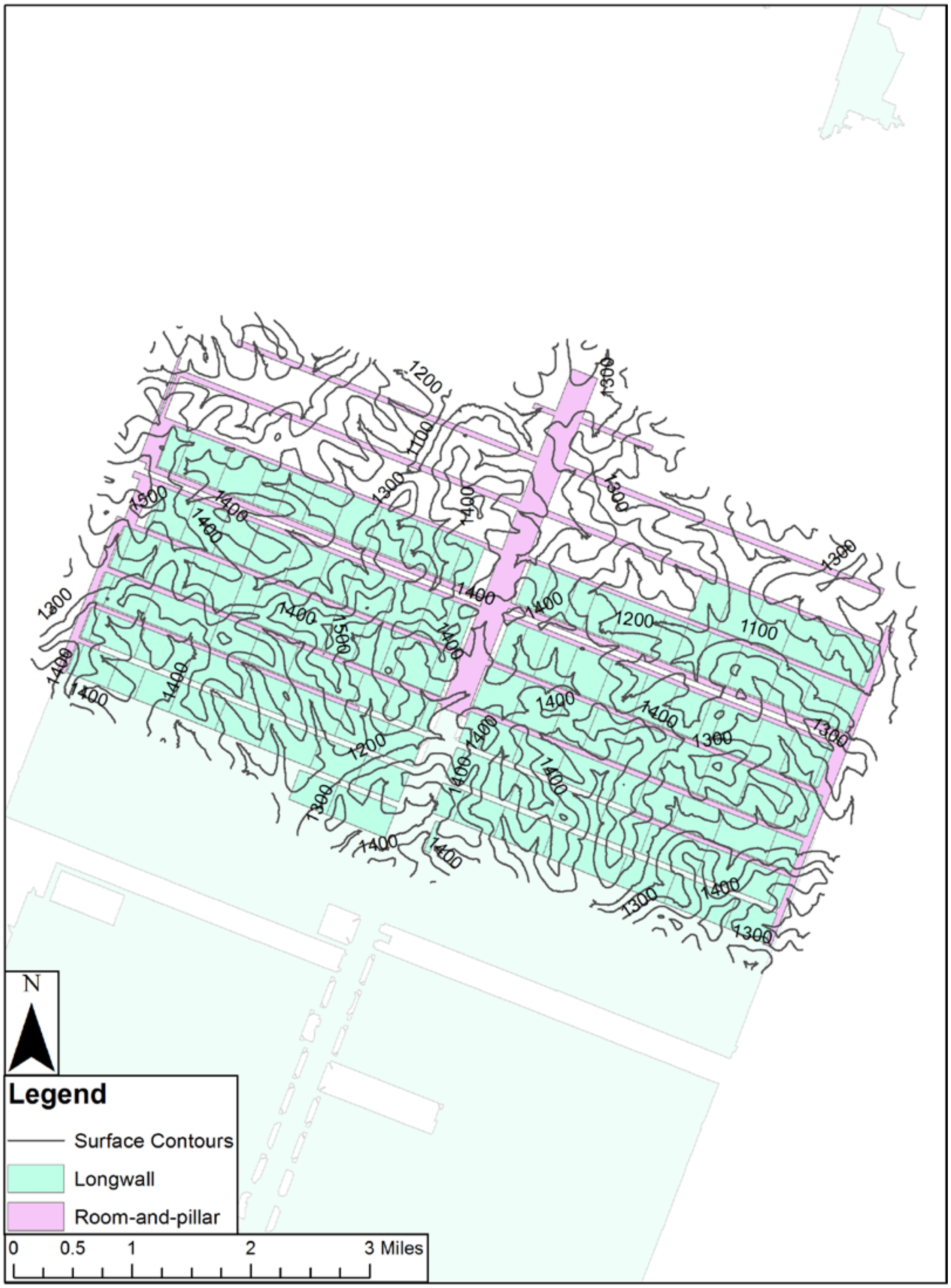


ENLOW FORK SATELITE IMAGERY

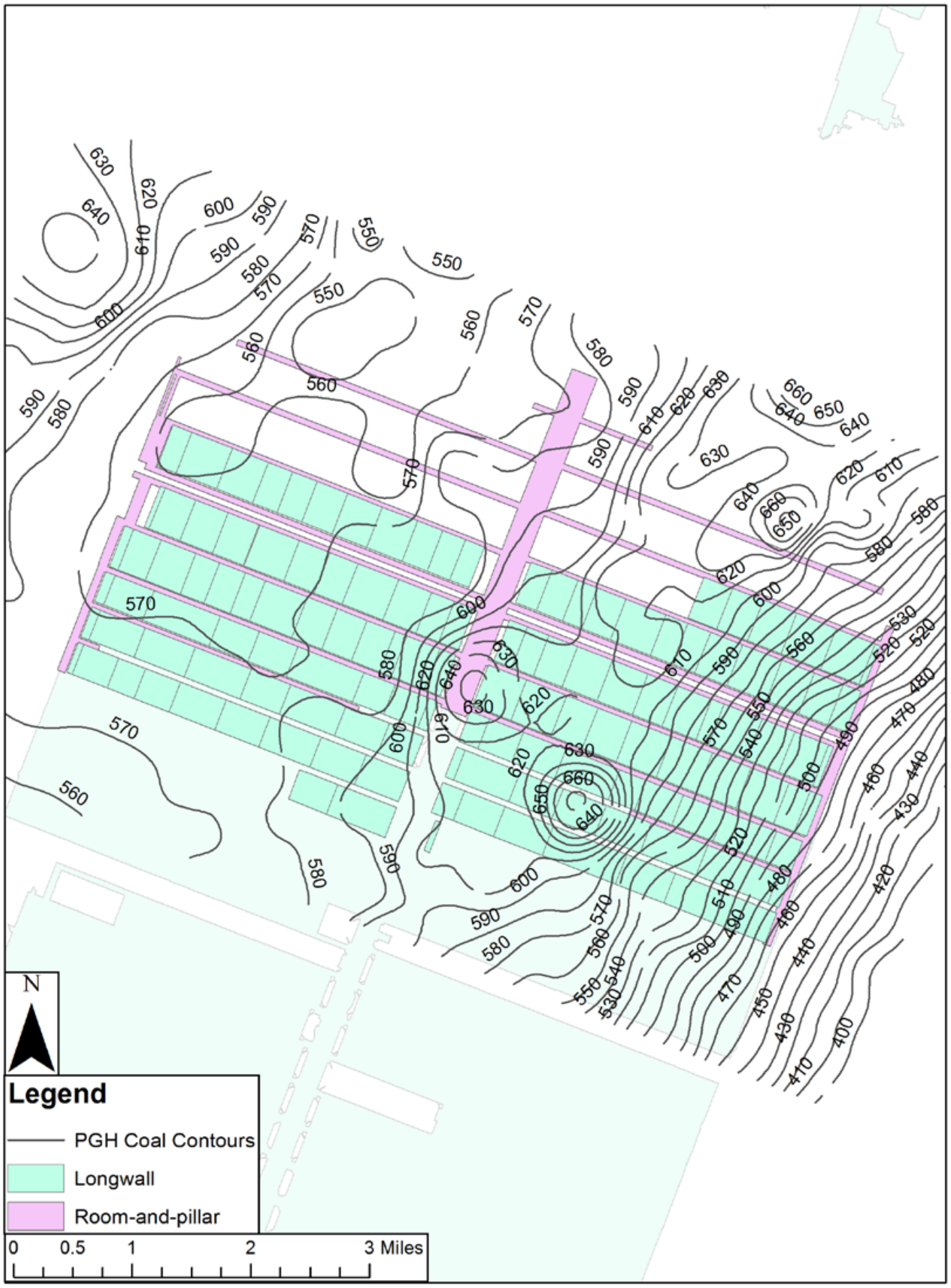
ENLOW FORK ROADS AND STREAMS



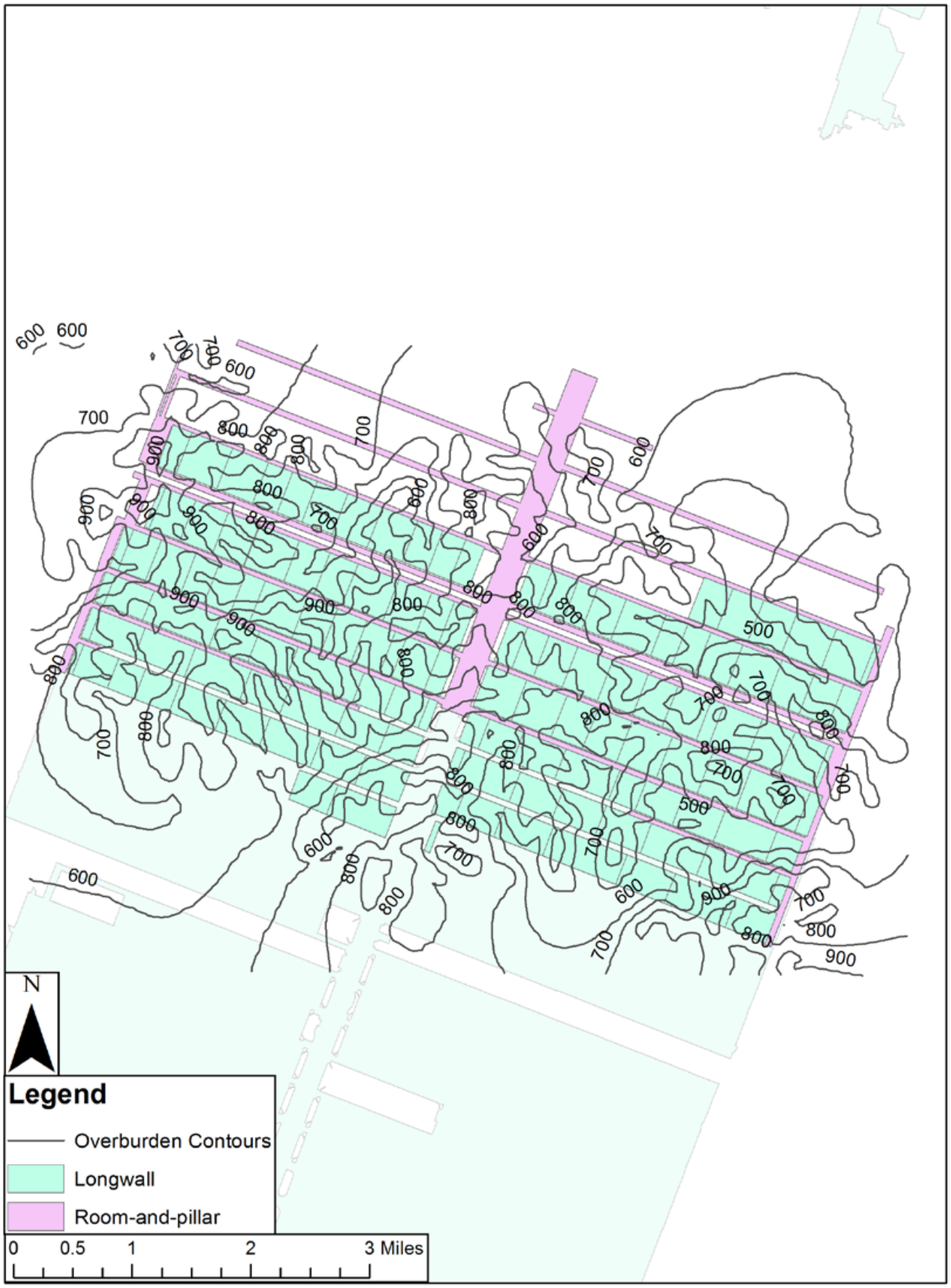
ENLOW FORK SURFACE CONTOURS



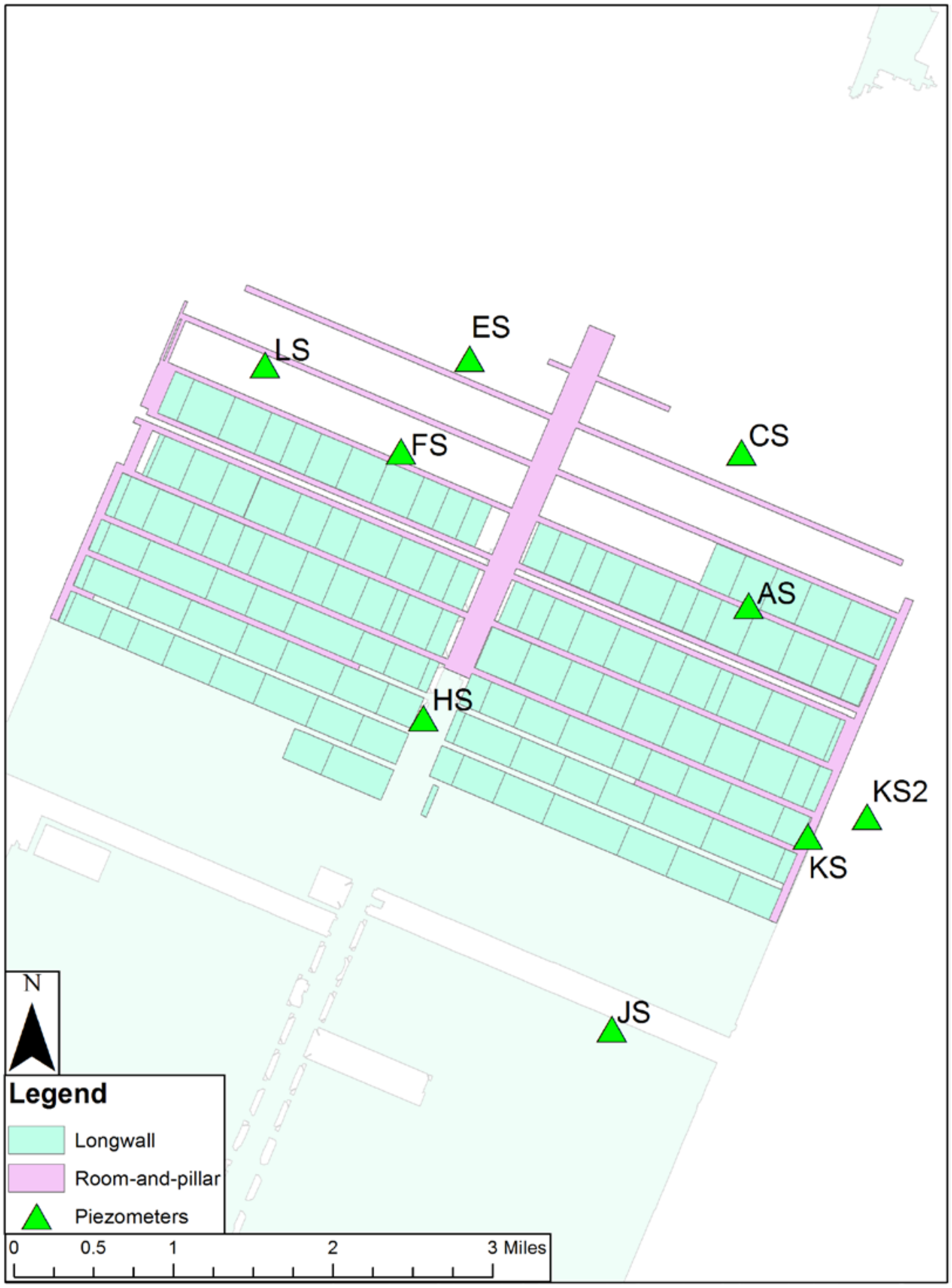
ENLOW FORK COAL CONTOURS



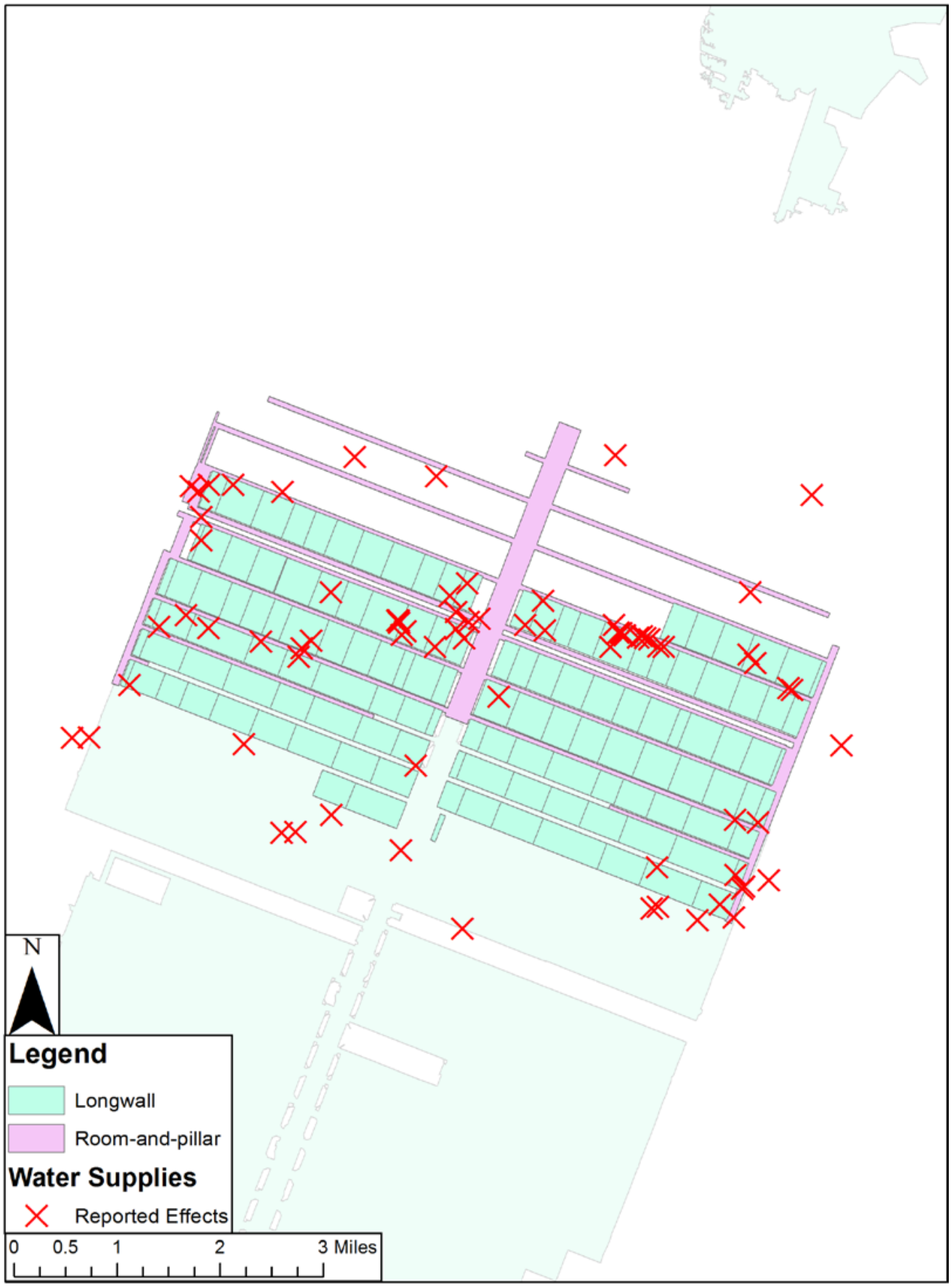
ENLOW FORK OVERBURDEN CONTOURS



ENLOW FORK PIEZOMETER LOCATIONS



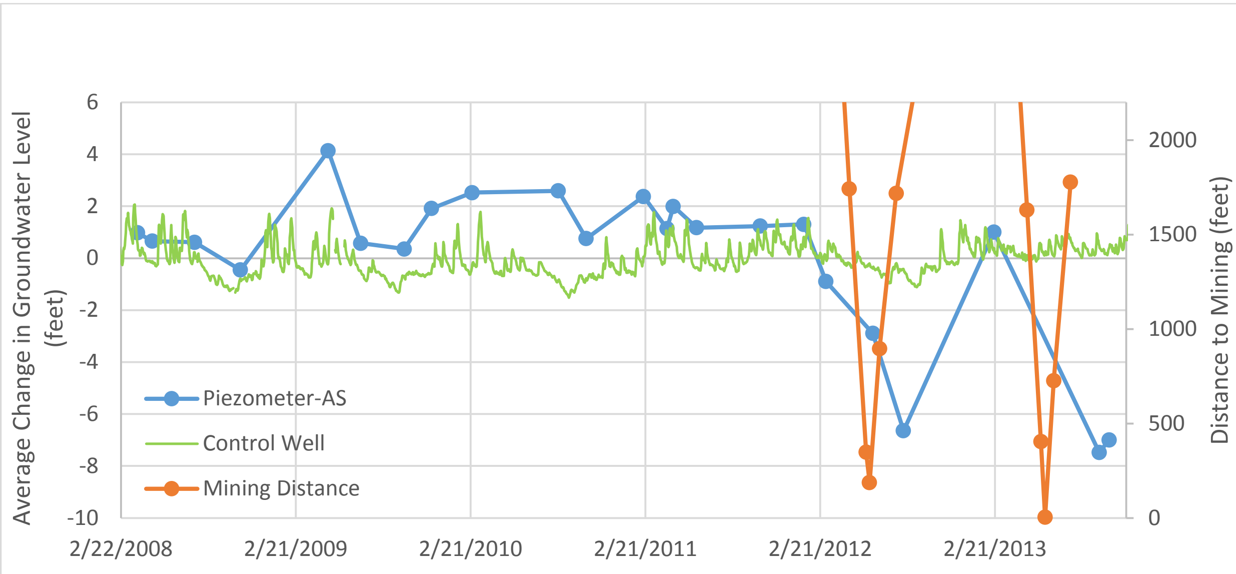
ENLOW FORK REPORTED WATER SUPPLY EFFECTS



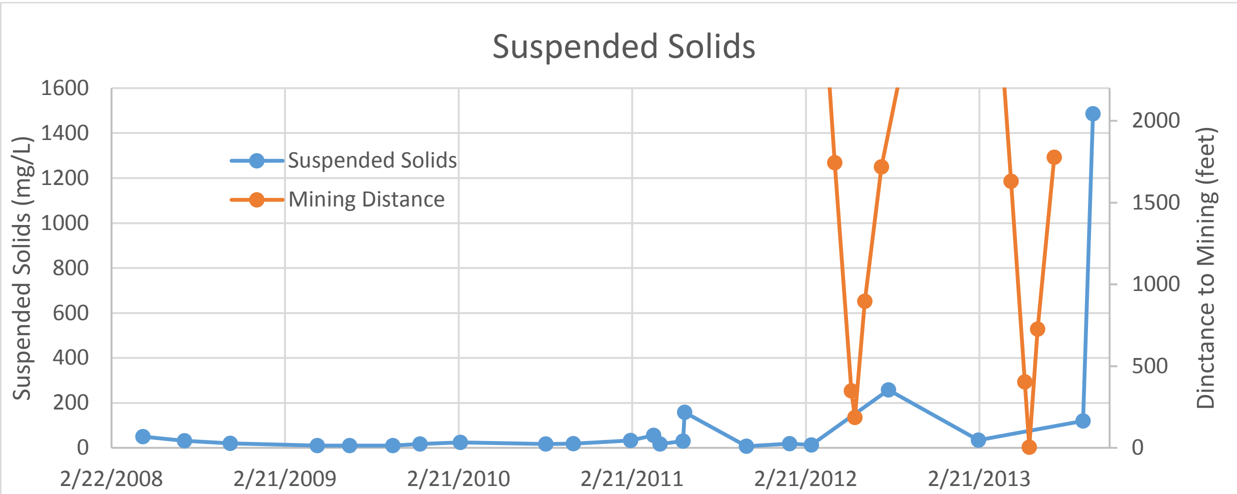
C.2 ENLOW FORK PIEZOMETER GROUNDWATER LEVELS AND QUALITY

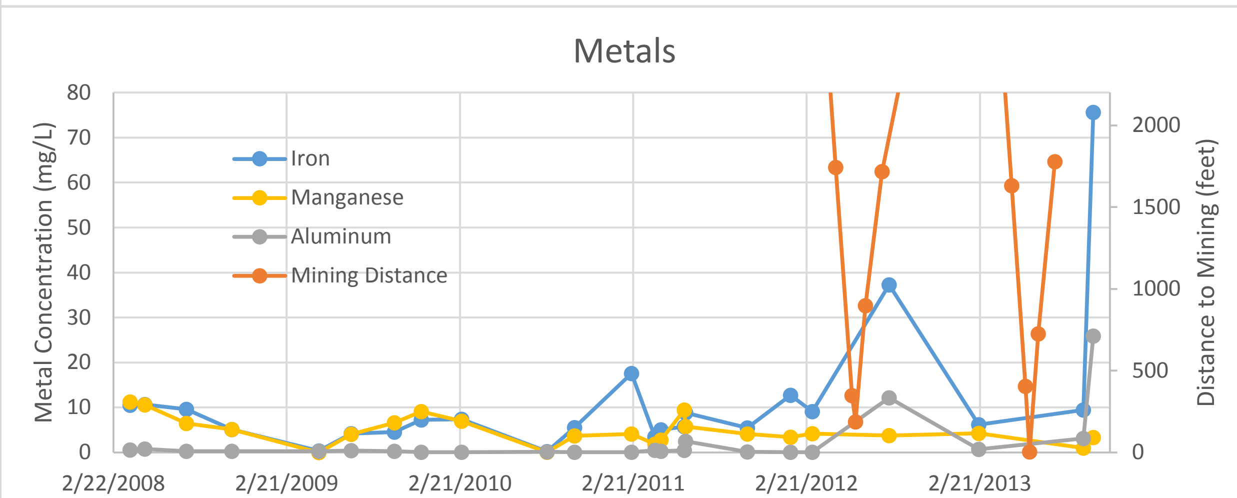
The following graphs display groundwater levels and quality information for piezometers not explained in the analysis. The graphs are similar to those of piezometer-HS and piezometer-FS. Groundwater levels are shown with comparison to the control well and distance to mining. Measures of quality are suspended solids, metals, and sulfate concentrations.

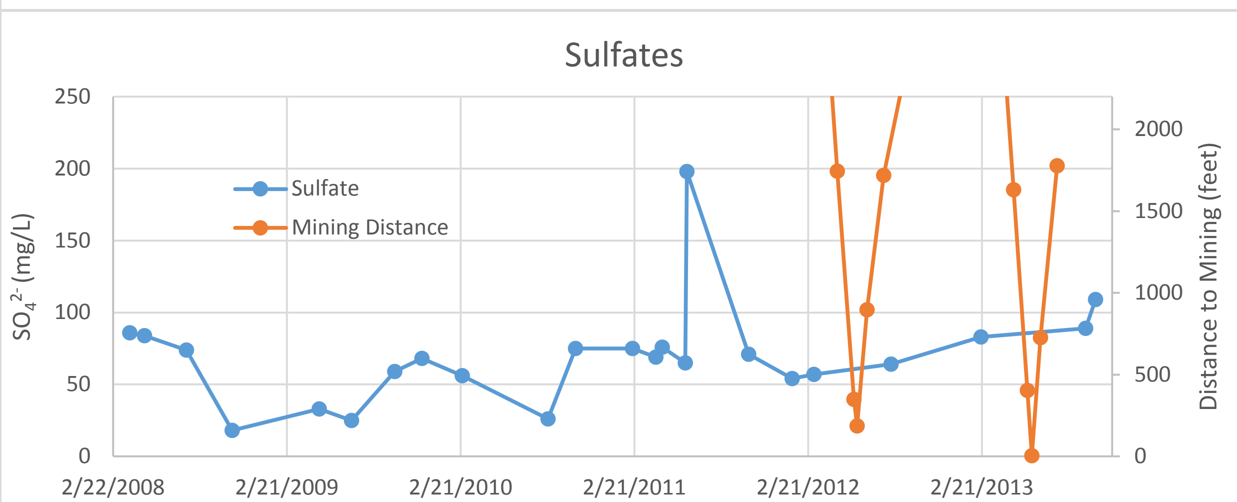
PIEZOMETER-AS GROUNDWATER LEVELS



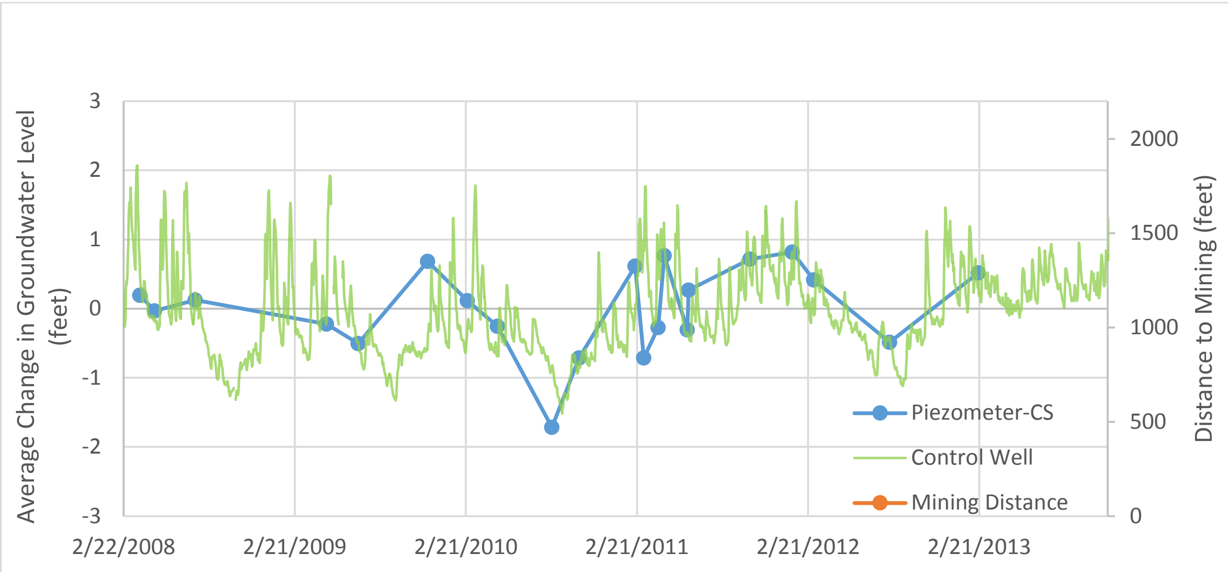
PIEZOMETER-AS GROUNDWATER QUALITY



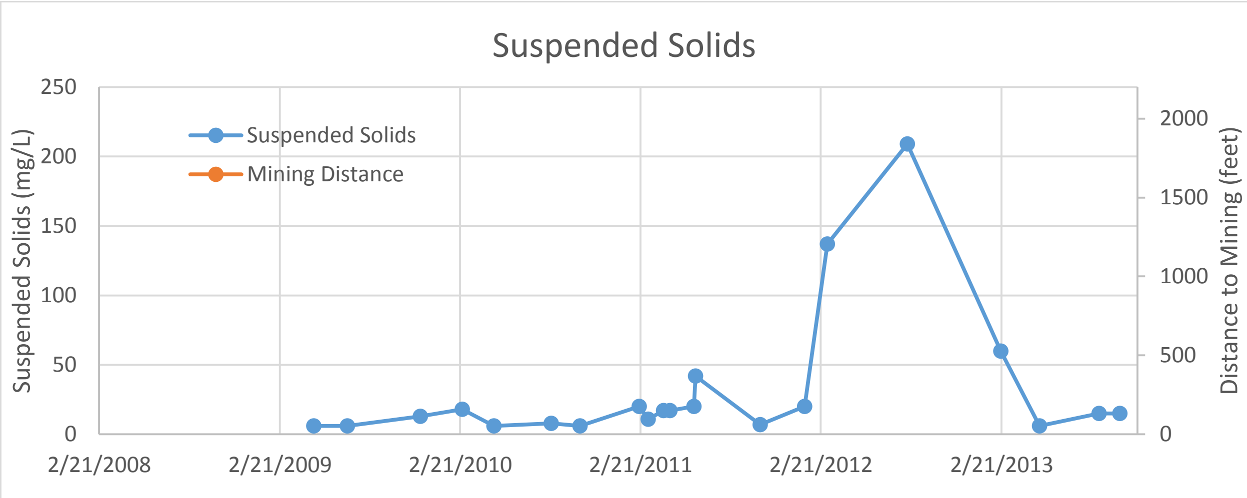


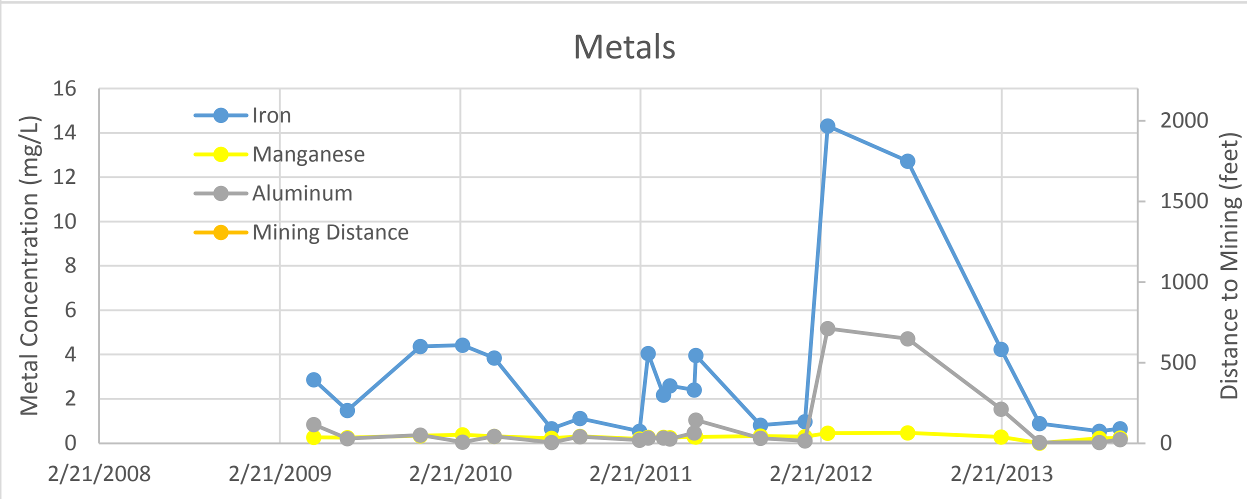


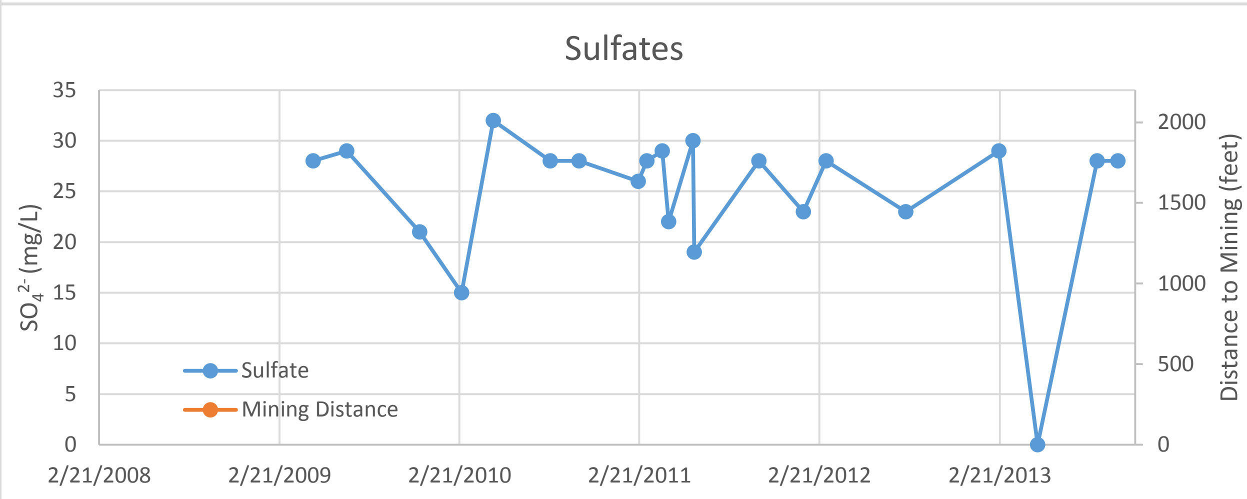
PIEZOMETER-CS GROUNDWATER LEVELS



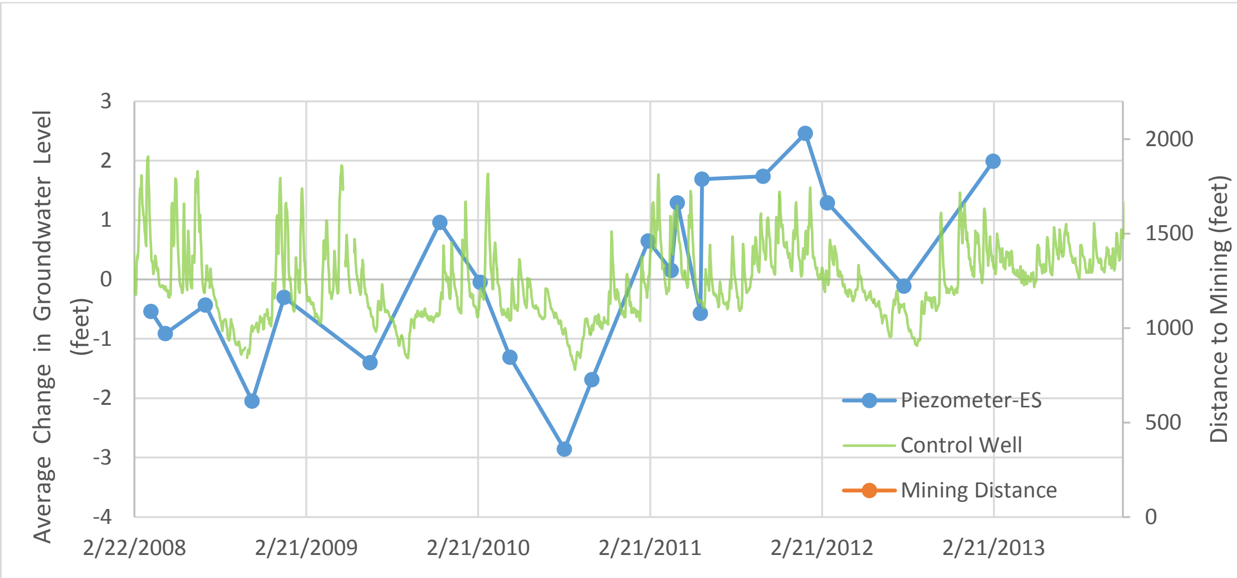
PIEZOMETER-CS GROUNDWATER QUALITY



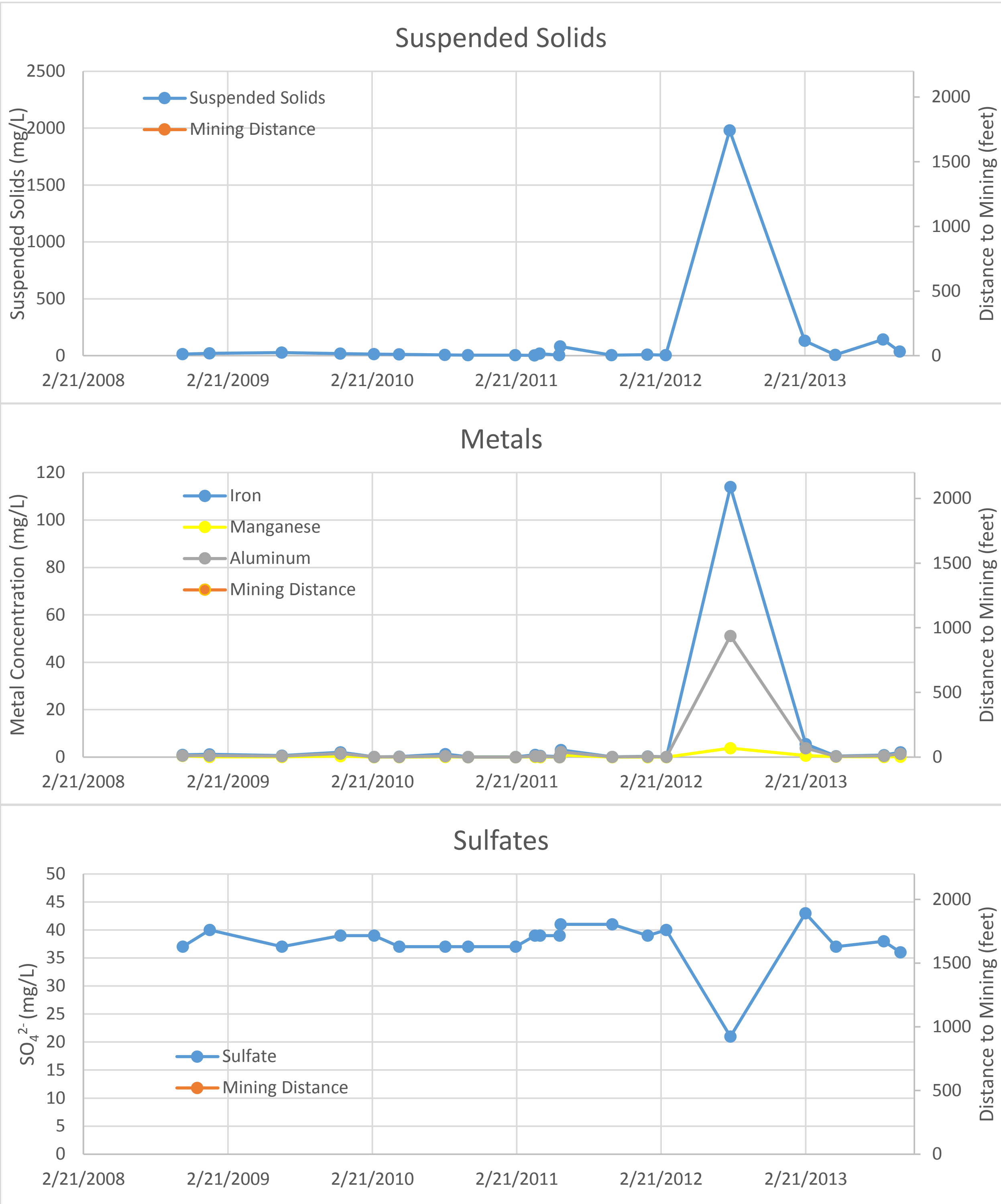




PIEZOMETER-ES GROUNDWATER LEVELS



PIEZOMETER-ES GROUNDWATER QUALITY



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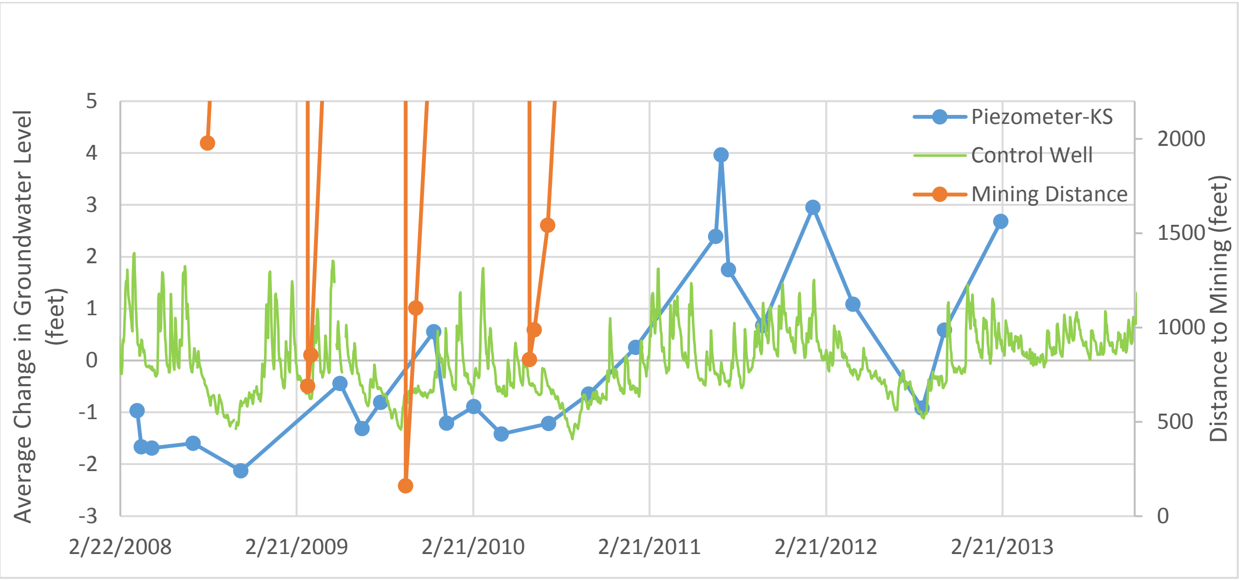

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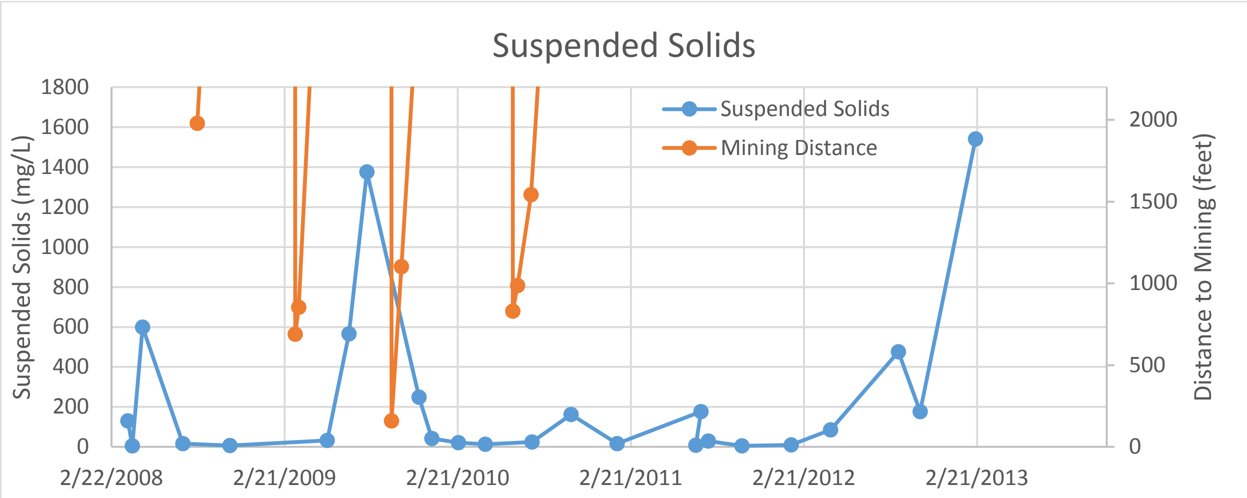
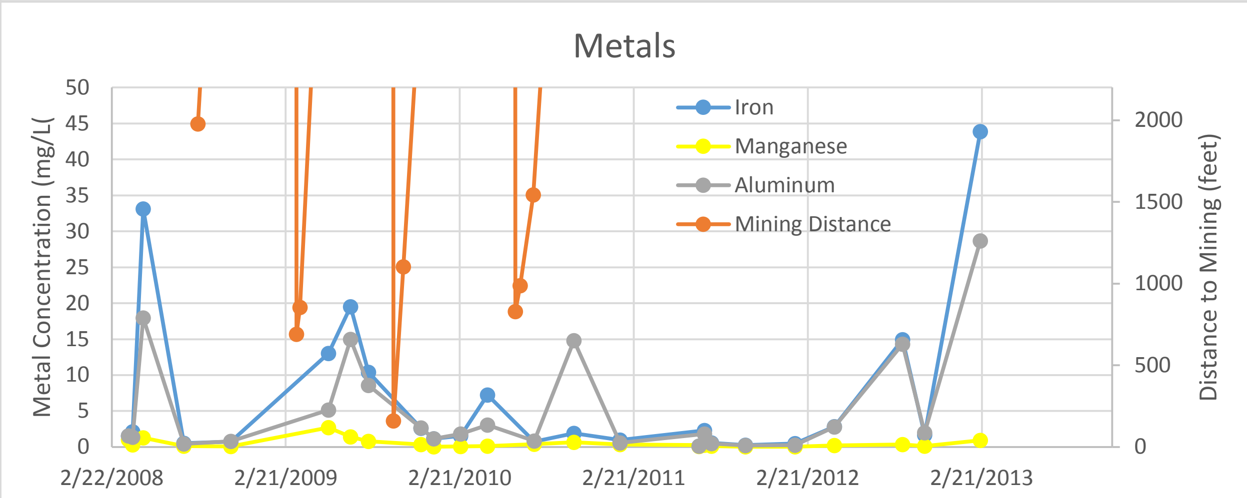
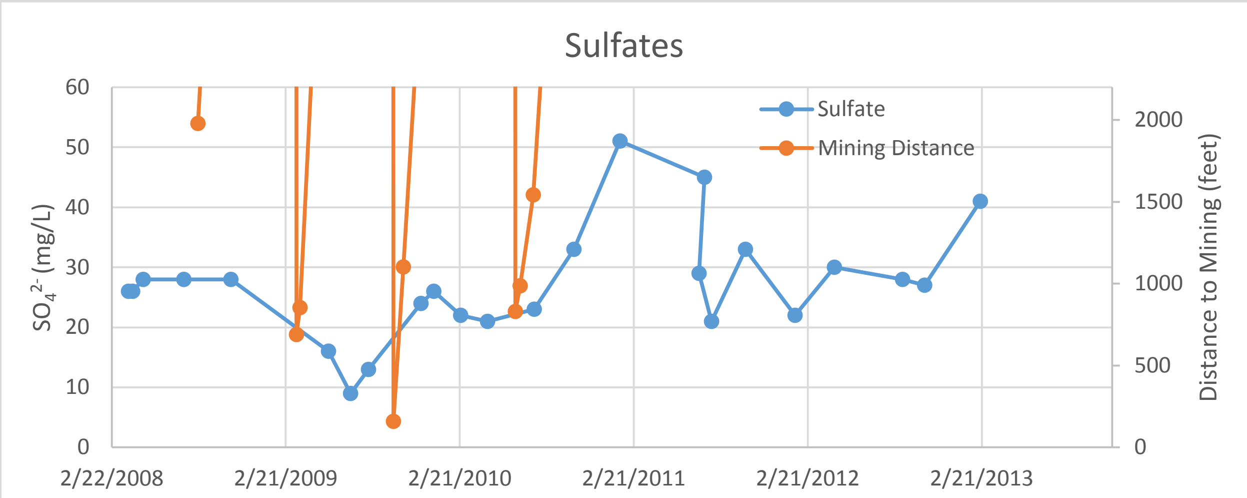
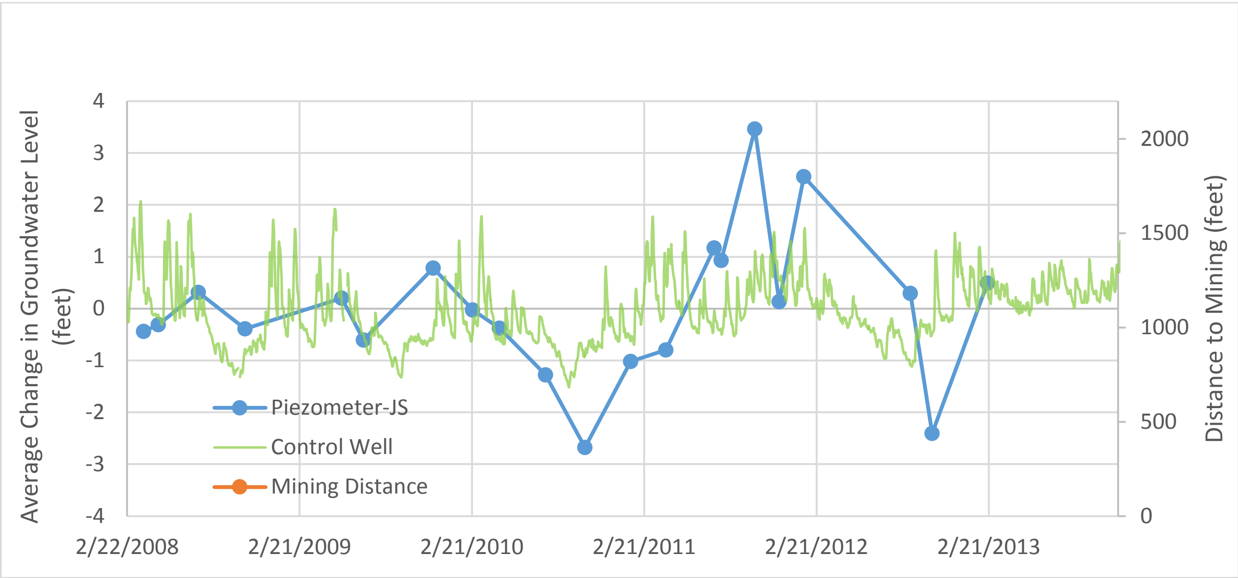


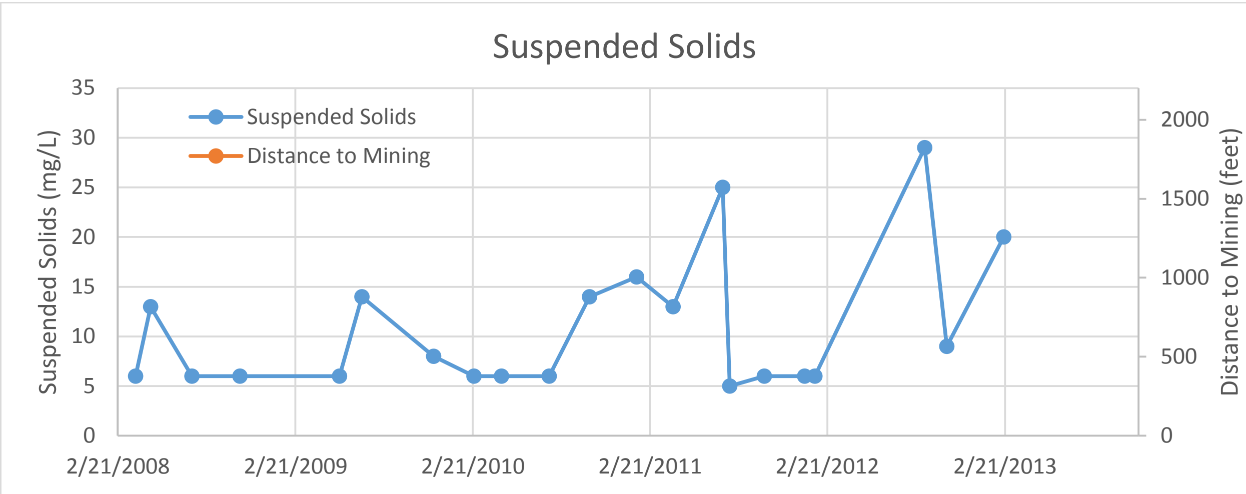


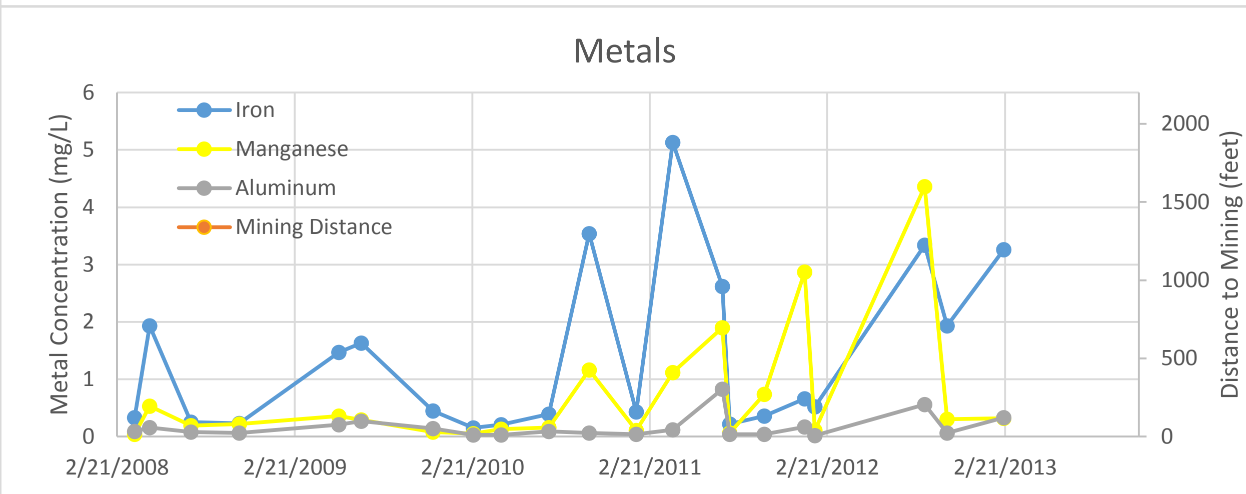


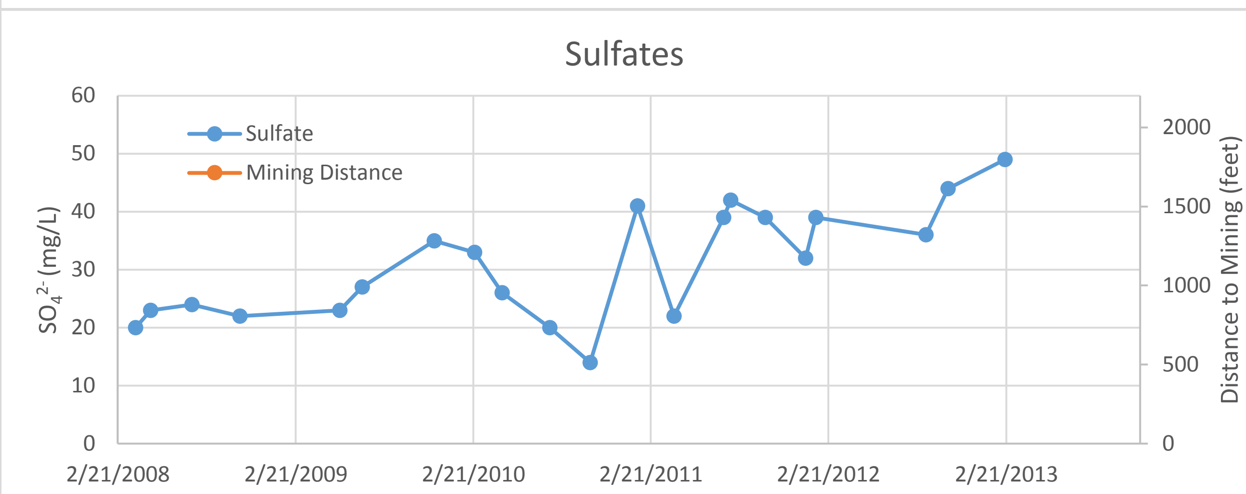
PIEZOMETER-JS GROUNDWATER LEVELS



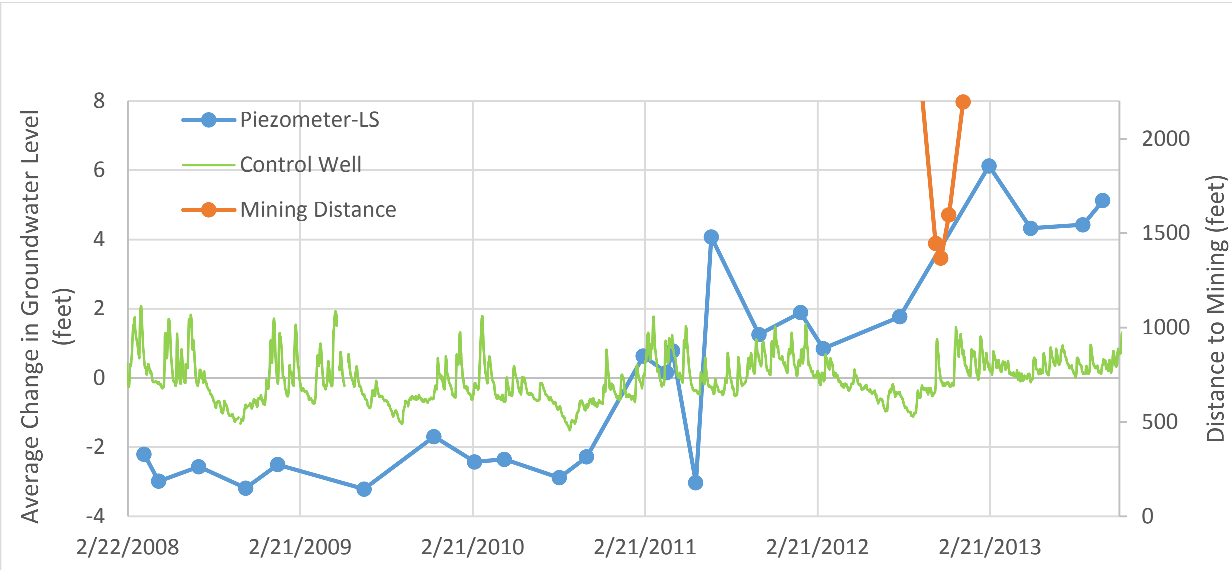
PIEZOMETER-JS GROUNDWATER QUALITY



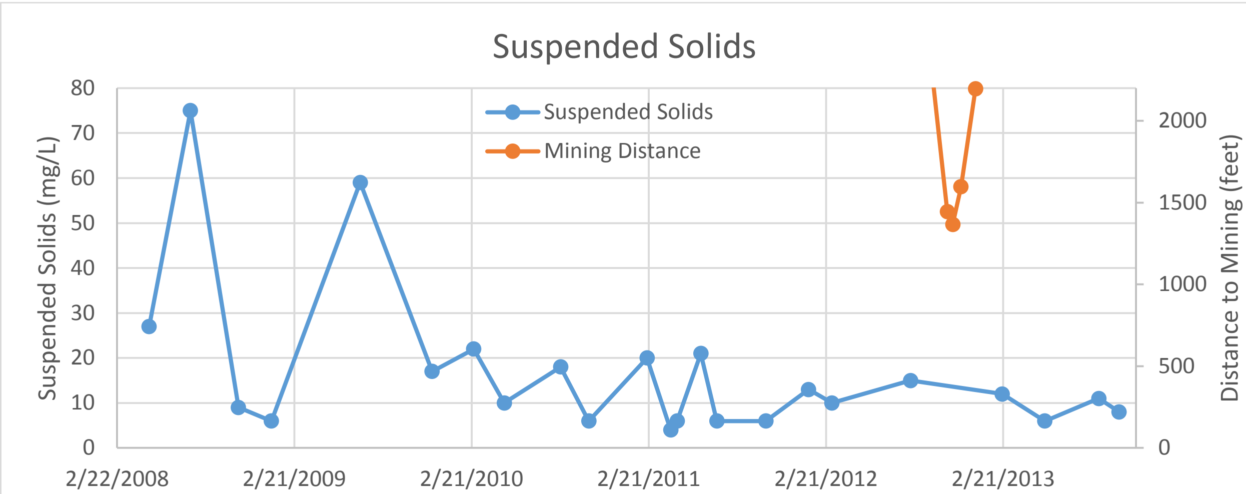


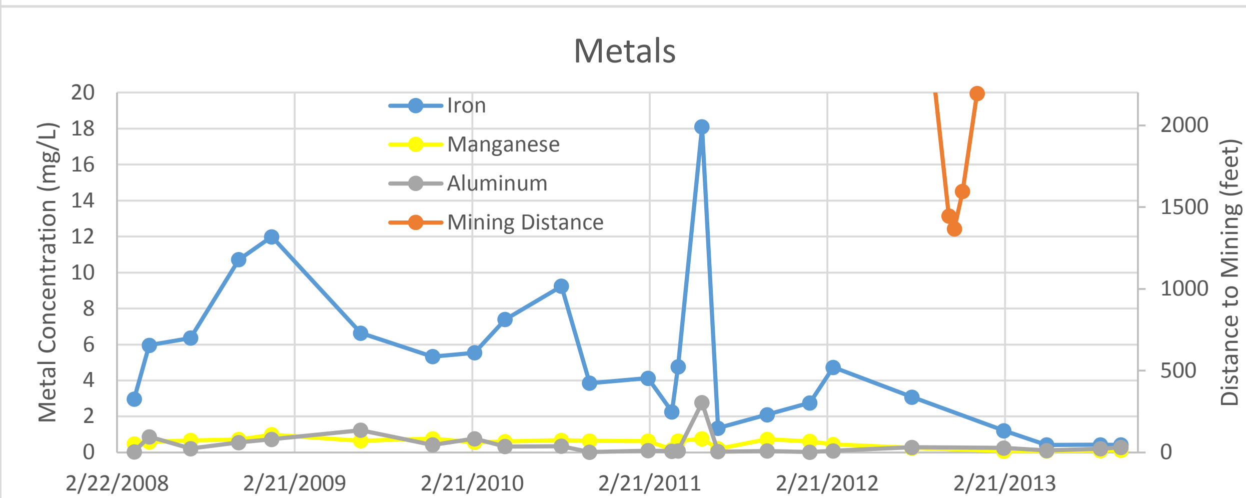


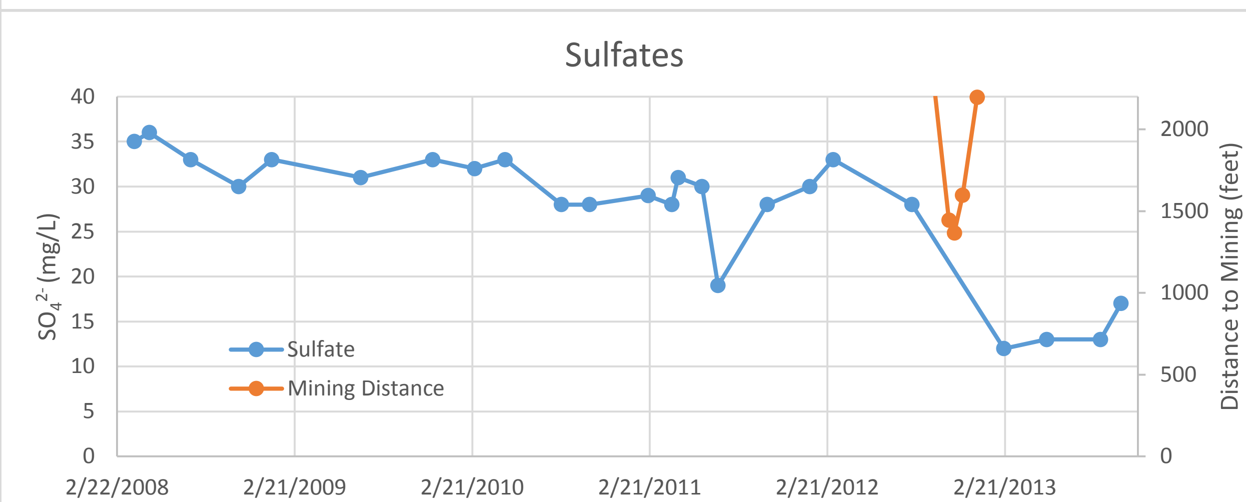
PIEZOMETER-LS GROUNDWATER LEVELS



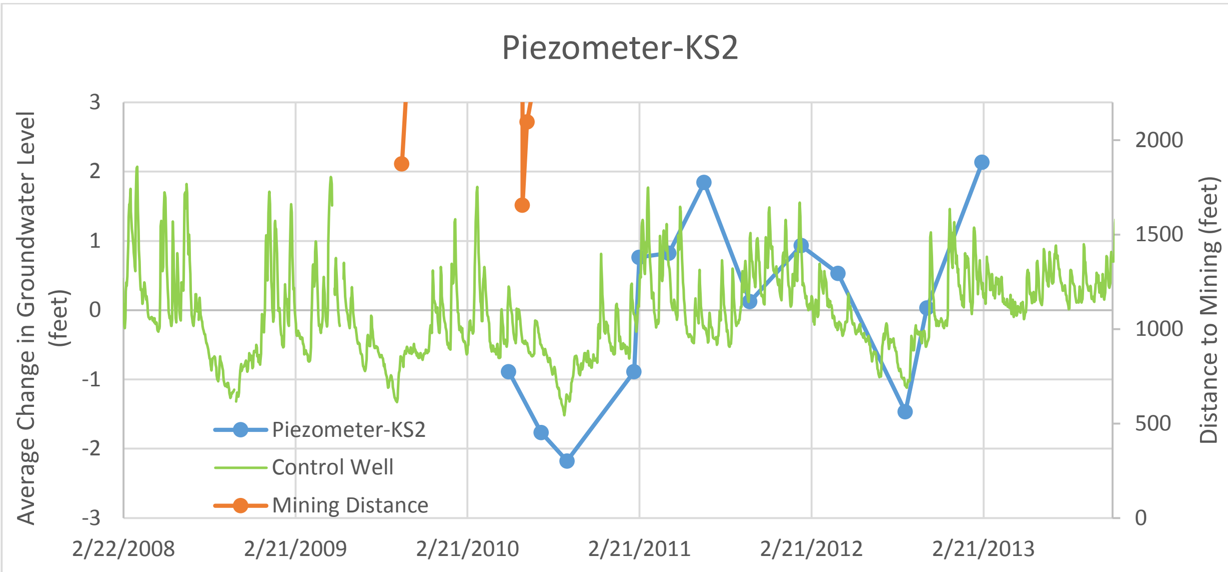
PIEZOMETER-LS GROUNDWATER QUALITY



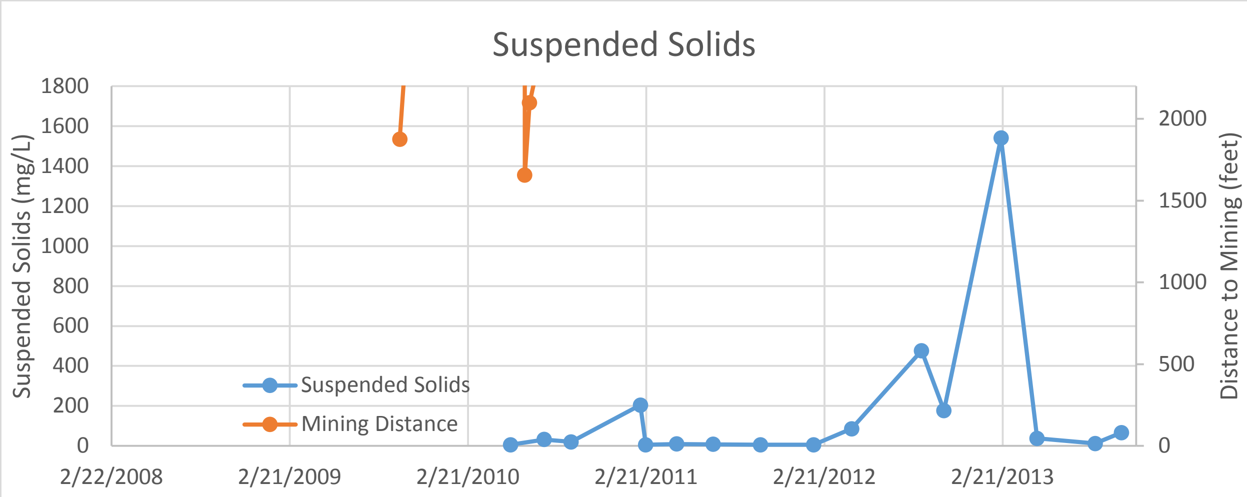


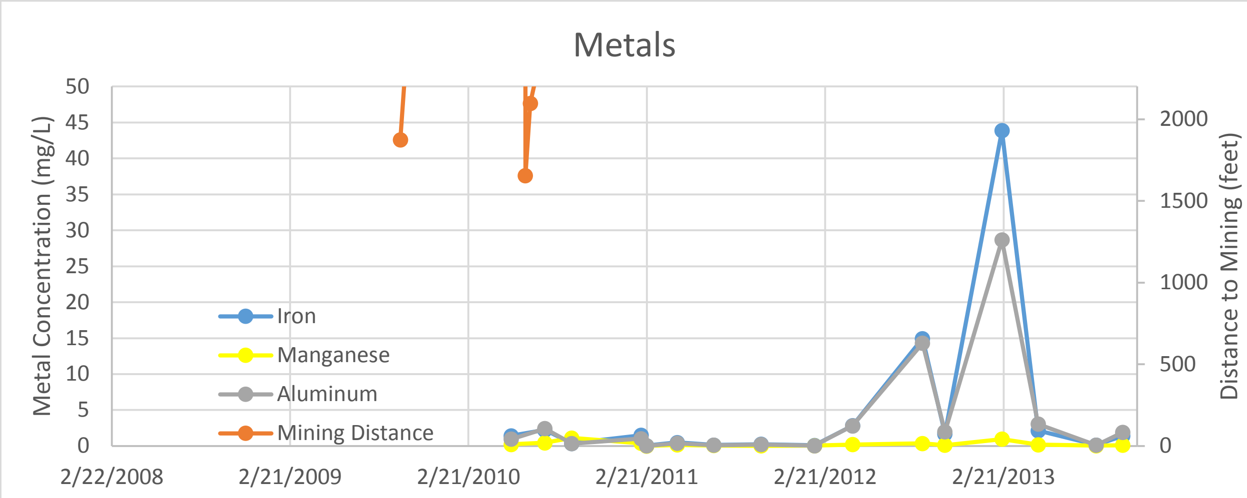


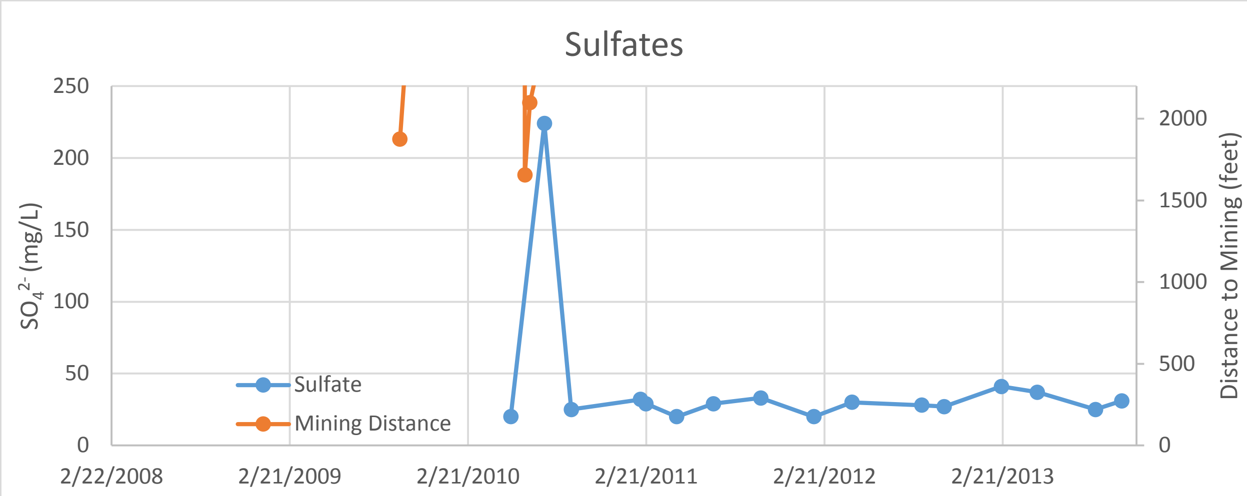
PIEZOMETER-KS2 GROUNDWATER LEVELS



PIEZOMETER-KS2 GROUNDWATER QUALITY





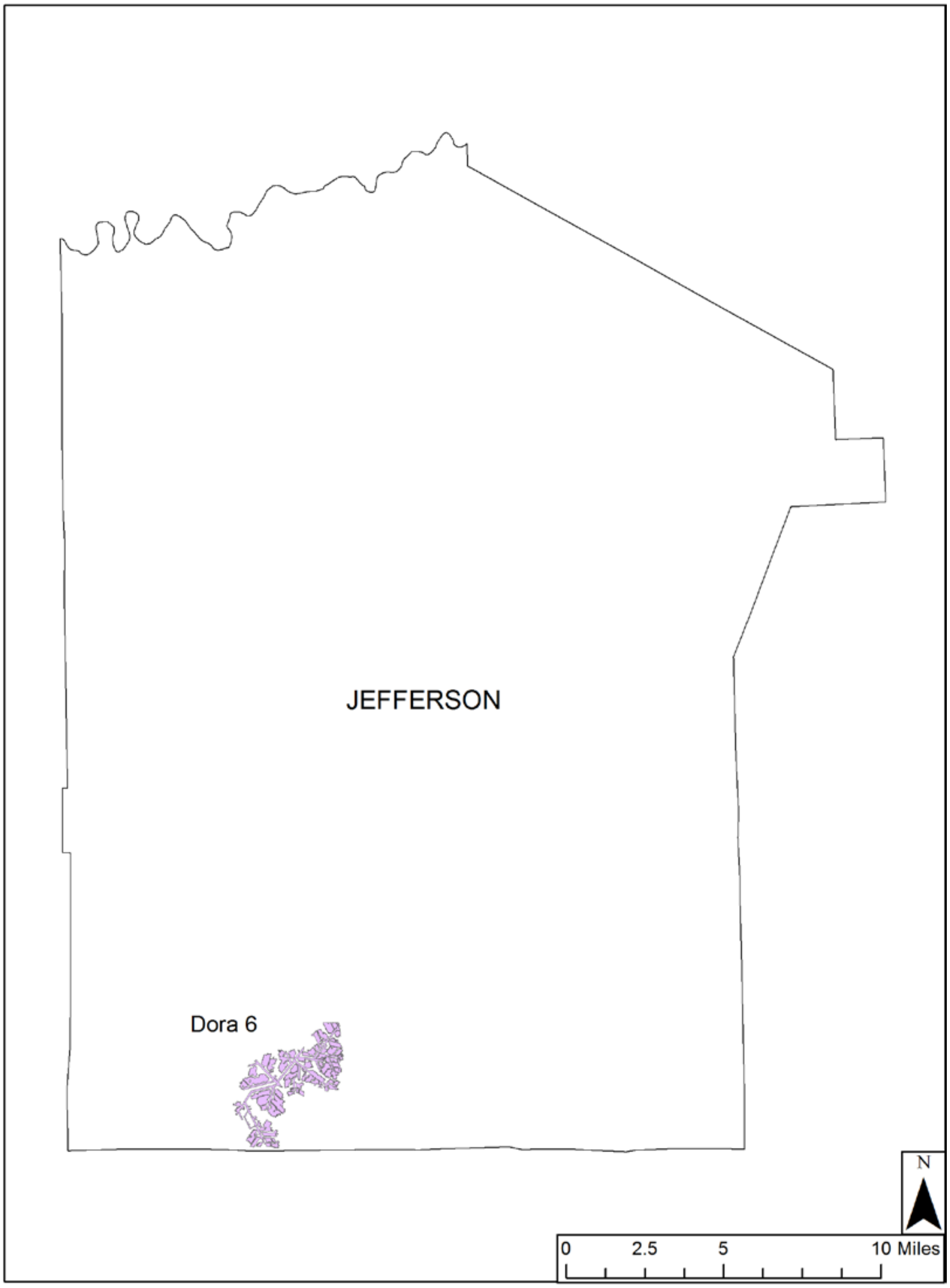


APPENDIX D

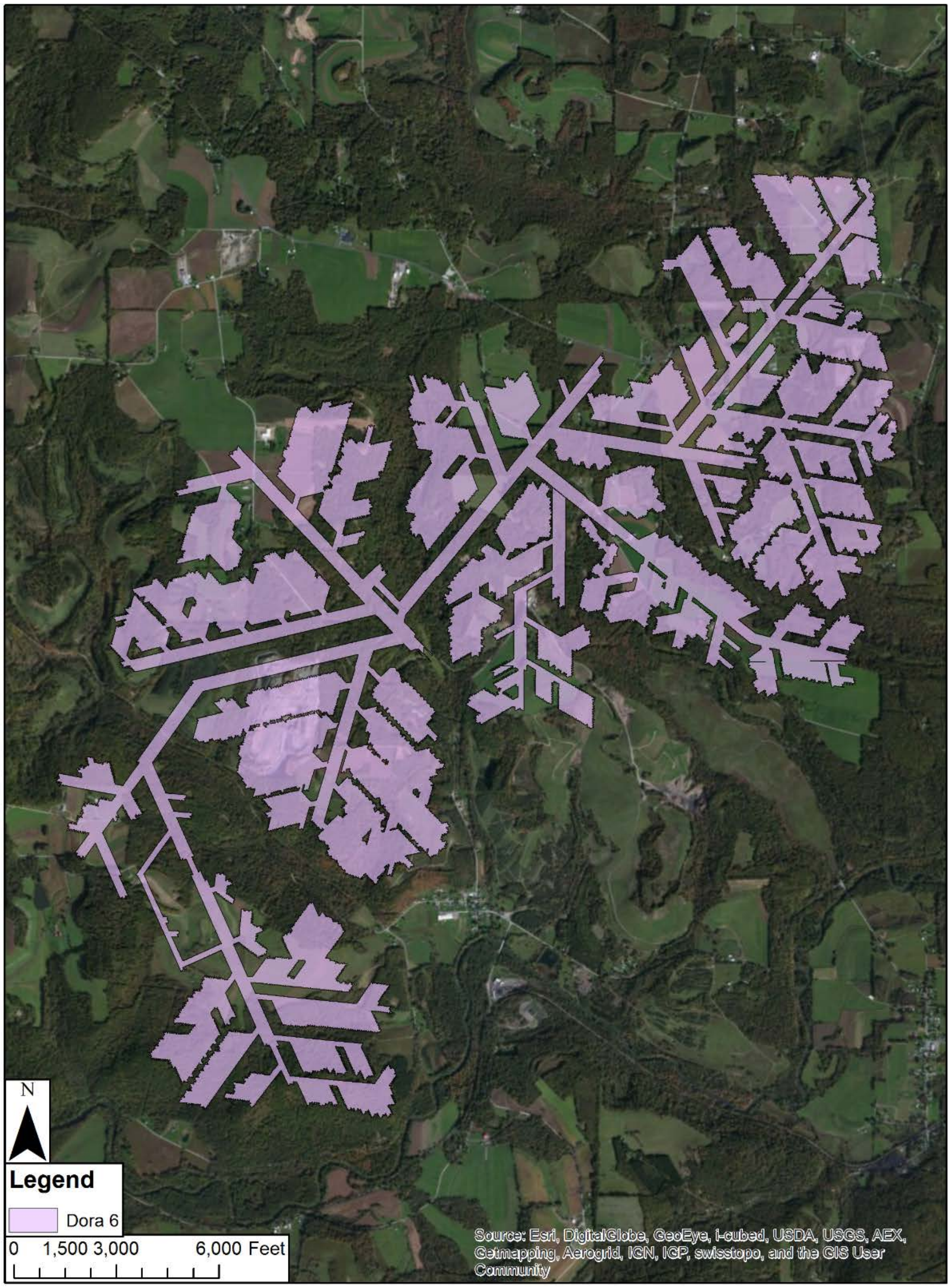
D.1 DORA 6 MAPS

The following set of maps include information related to Dora 6 mine. The maps include county location, satellite imagery, roads and streams, surface contours, coal contours, and overburden contours. Also are the locations reported water supply impacts and the maximum mine pool elevation.

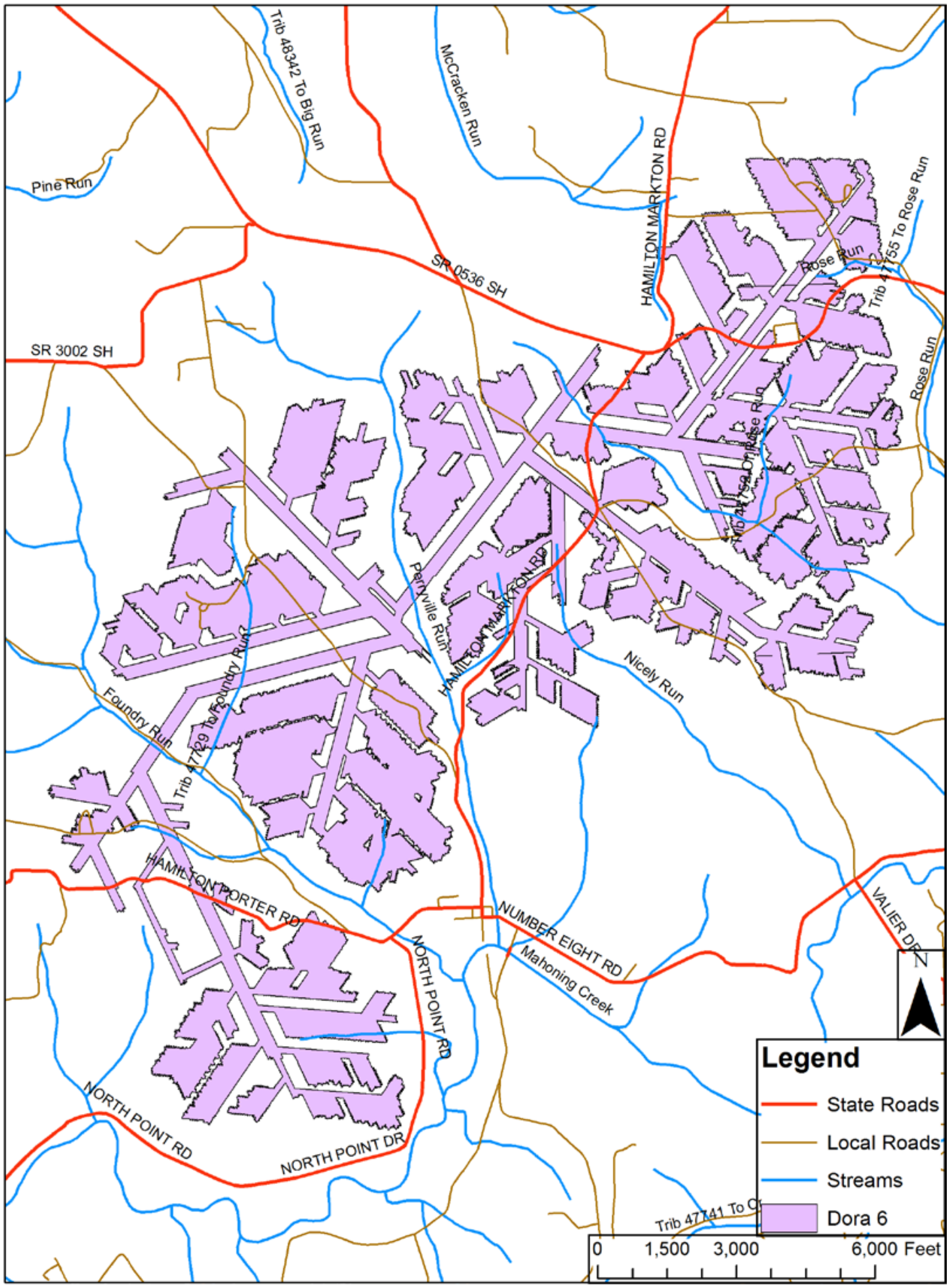
DORA 6 COUNTY LOCATION



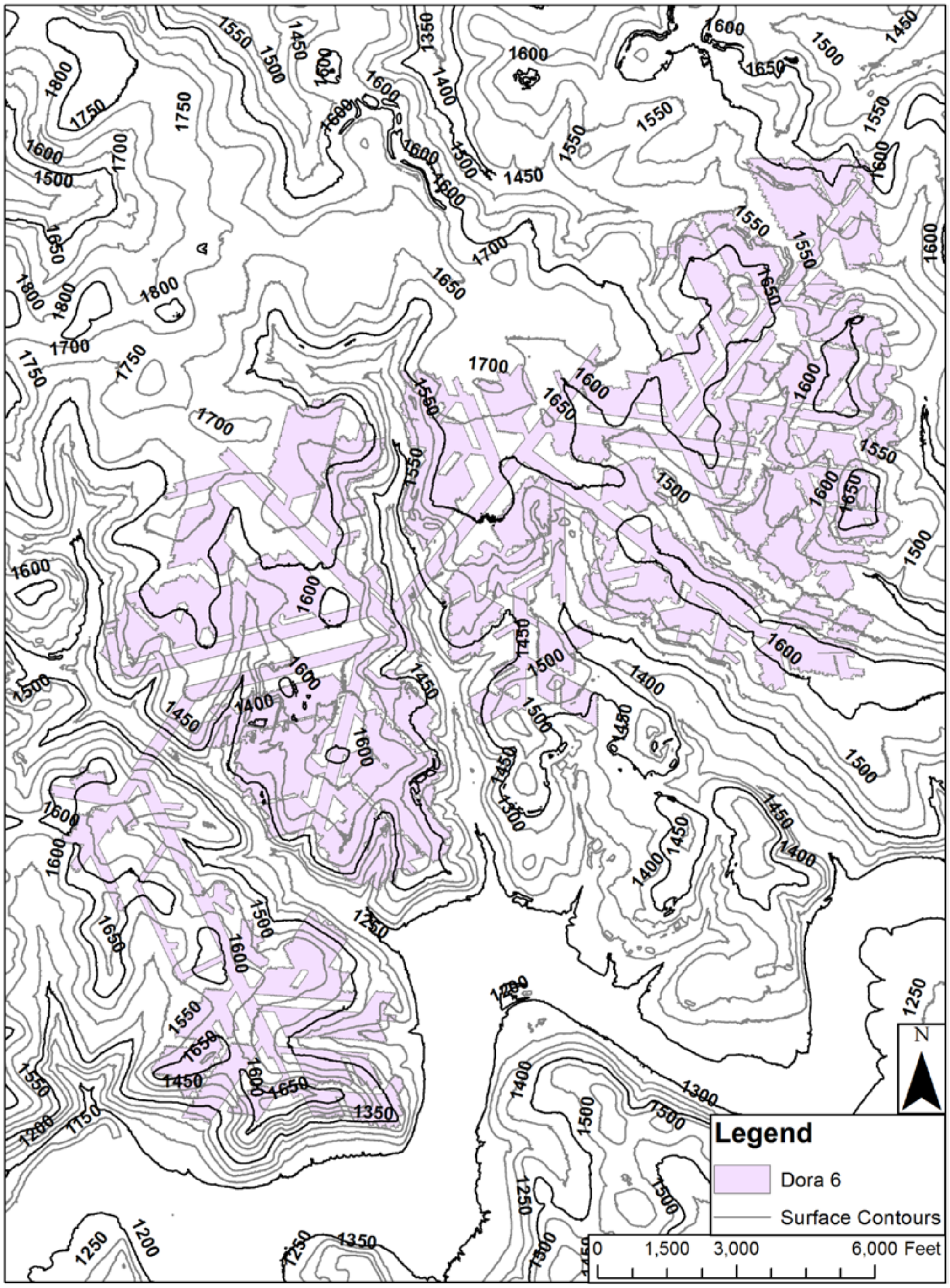
DORA 6 SATELITE IMAGERY



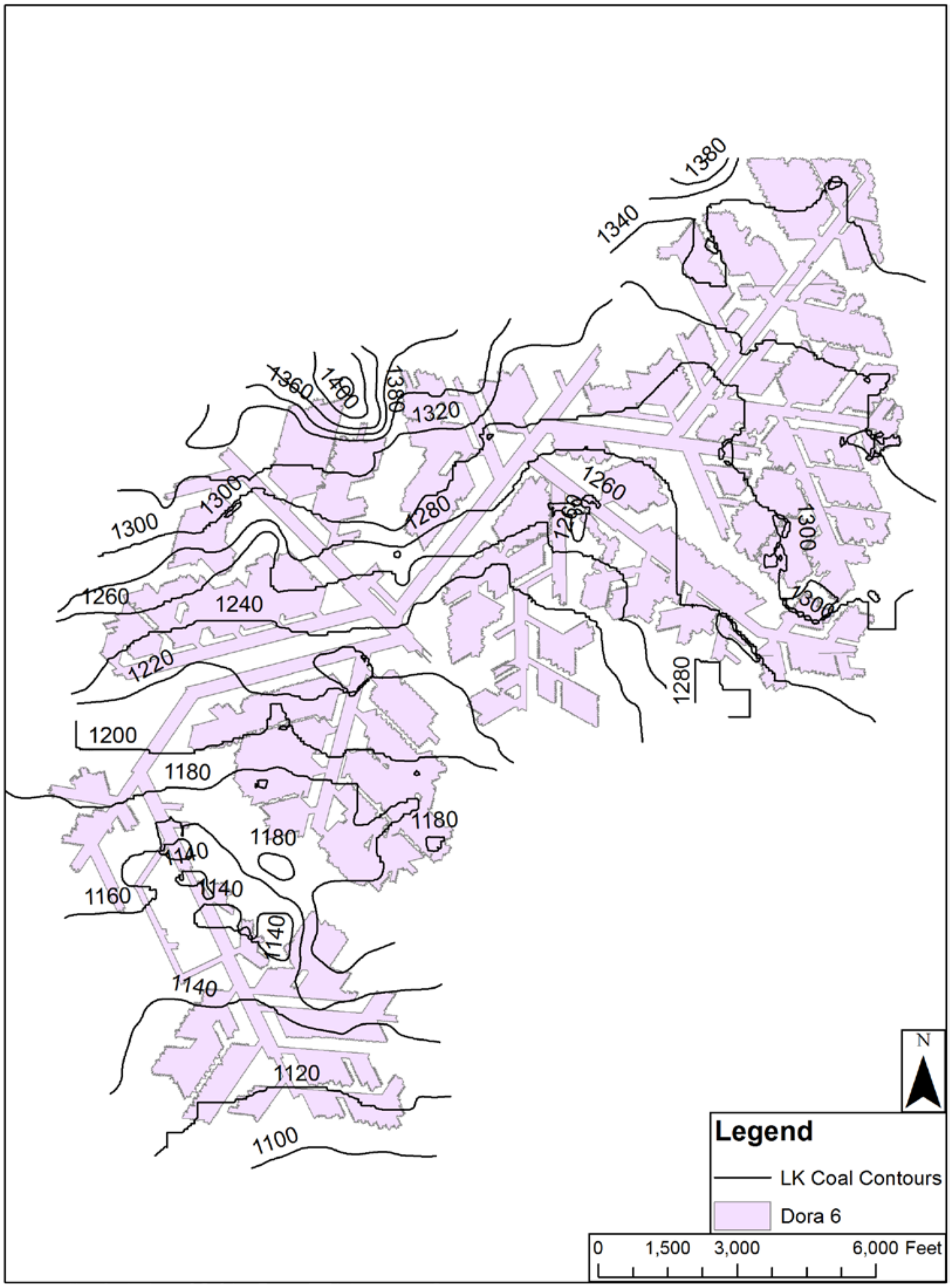
DORA 6 ROADS AND STREAMS



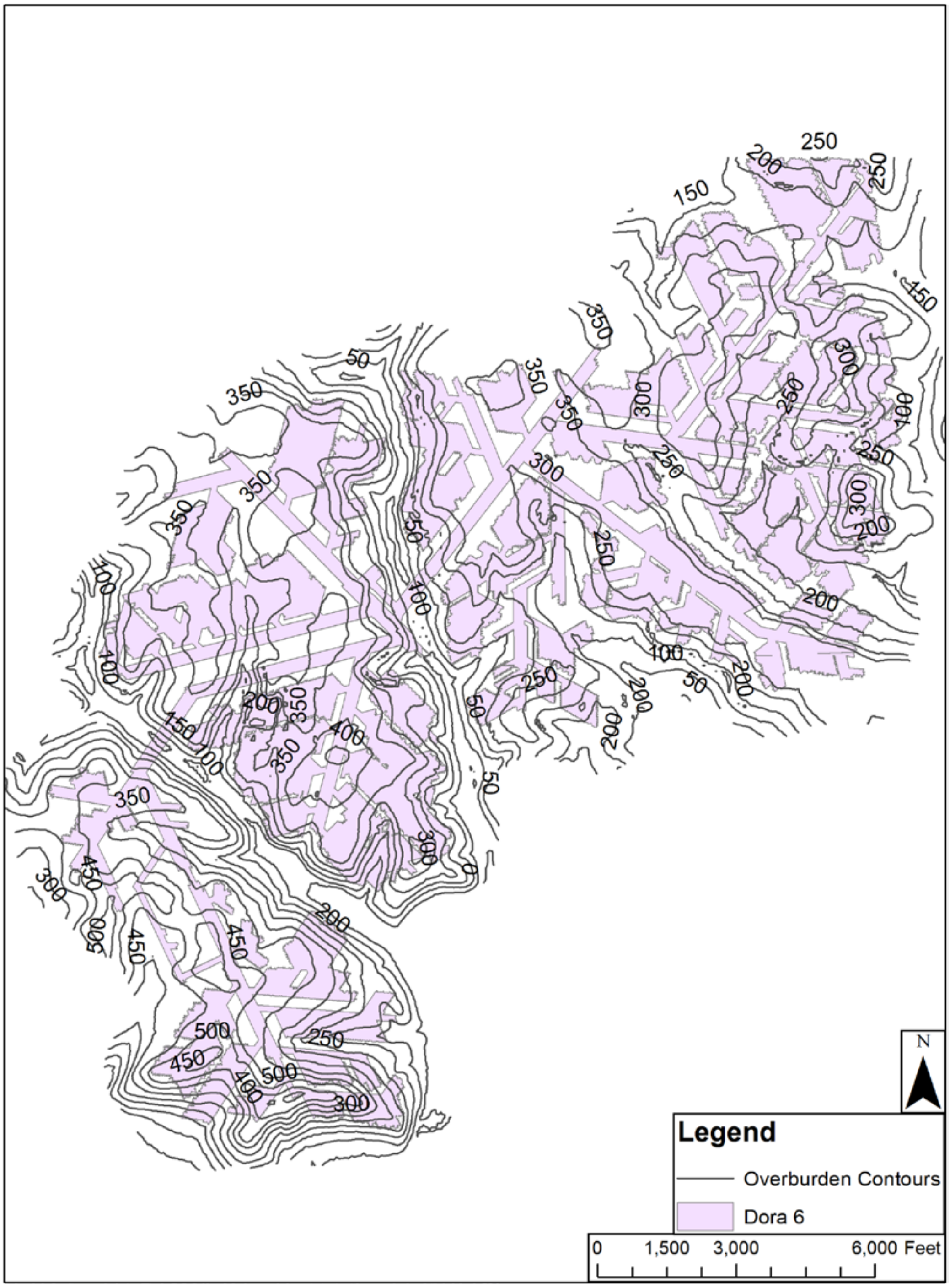
DORA 6 SURFACE CONTOURS



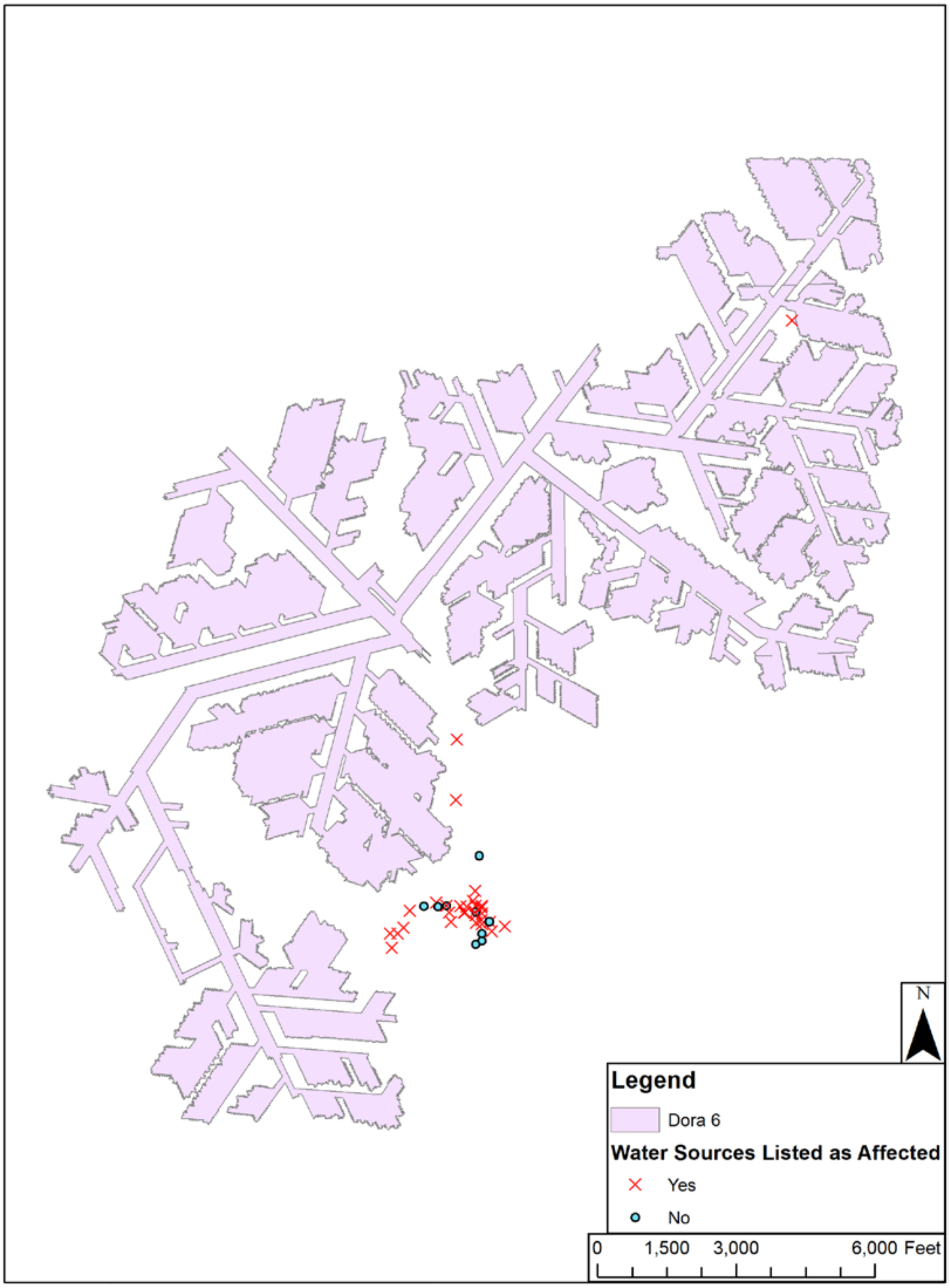
DORA 6 COAL CONTOURS



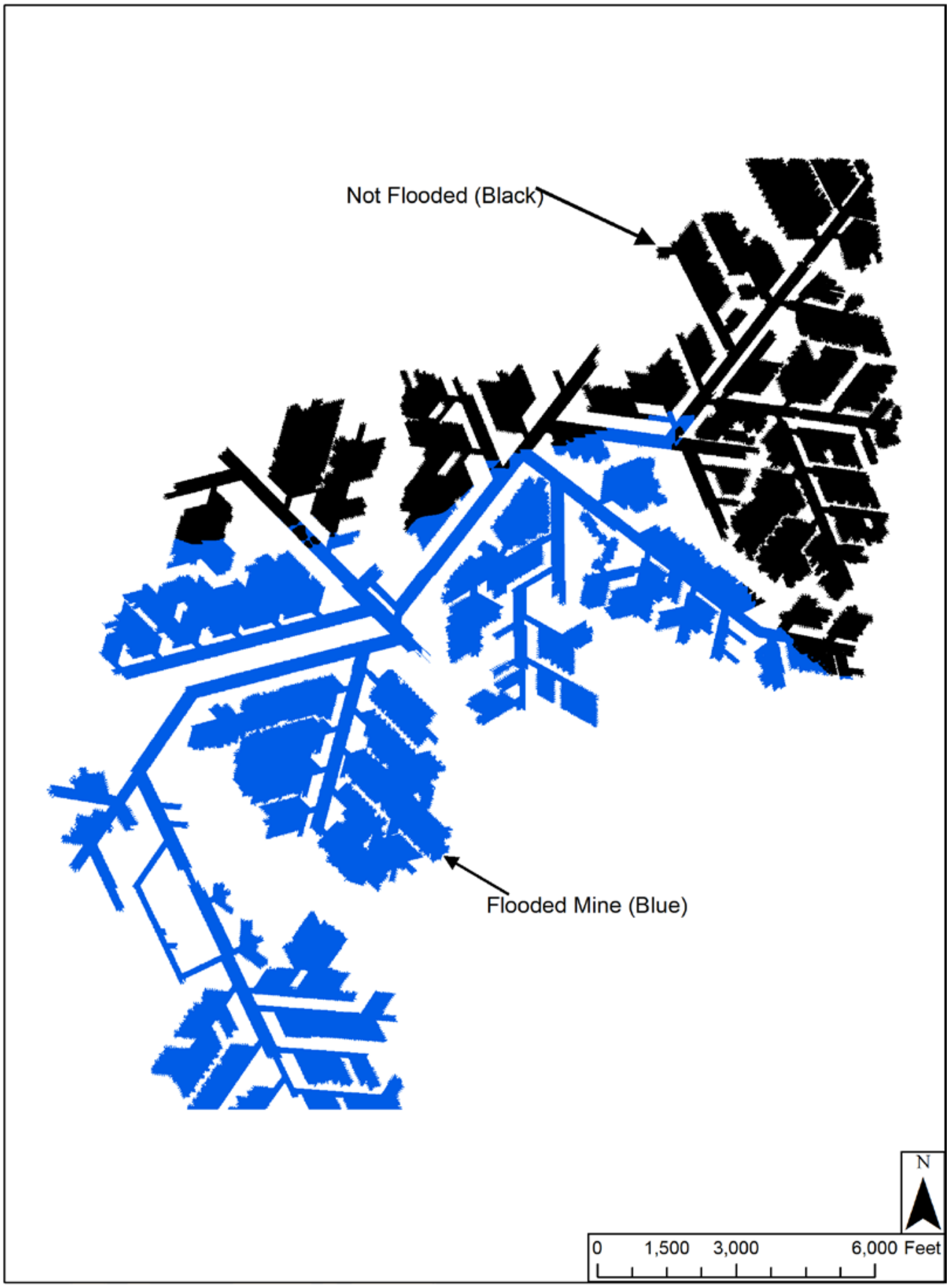
DORA 6 OVERBURDEN CONTOURS



DORA 6 REPORTED WATER SUPPLY IMPACTS



DORA 6 MAXIMUM MINE POOL ELEVATION



D.2 DORA 6 GEOLOGIC DATA

The following contains information regarding geology around the Dora 6 mine. The data includes geology data from water wells drilled in the area and elevation profiles of the surface and Lower Kittanning coal contours. This information is used to help determine the location of a coal outcrop near the town of Hamilton.

WATER WELL LOG NO. 1

Department of Environmental Resources | **TOPOGRAPHIC AND GEOLOGIC SURVEY** | **Water Well Inventory Report**

OFFICE USE ONLY

St. 42 Co ______ Lat ______ Long ______ | Hydrologic Unit ______ Topo. ______

Seq ______ Acc. ______ MeD ______ Well No. ______ | Aquifer ______ Aquifer ______

Well Site Township Perry

County Jefferson

Address or P.O. Box Hamilton

Well Owner last name Cook first name Harry

If owner's address is other than well site address indicate on reverse.

Ownership ______ (CIRCLE ONE) private, city, corp/co., state, federal, county, other ______

Water Use ______ (CIRCLE ONE) residential, public, industry, irrigation, stock, institution, bottled, commercial, other ______

Well Use ______ (CIRCLE ONE) water supply, dry hole, recharge, test, heat pump, observation, monitoring, destroyed, other ______

Saltwater zones ______ No: ______ Yes ______ depth ______

Chemical/Biological Analysis made: Yes: ______ No ✓

Well Depth 110 ft. Well Diameter 6 1/4 in.

Casing Length 40 ft. Casing Length ______ ft

Casing Dia. 6 1/4 in Casing Dia. ______ in.

Casing material-steel, plastic, other ______ Casing material-steel, plastic, other ______

Type Construction: Rotary, Cable, Other ______

Well finish ______ (CIRCLE ONE) open, hole, screen, perforated/slotted, other ______

Well Grouted ______ Yes, ______ No, Material ______

Date Drilled month year 10/90

Water Level Before Test ______ ft.

Level at End of Test ______ ft.

Yield 60 gpm

Test Yield Method ______ (CIRCLE ONE) bailed, blown, or pumped, meter, orifice, watch and bucket, other ______

Drawdown ______ ft.

Length of Test ______ hr. ______ min.

Depth to Bedrock 37 ft. Landform at Site (CIRCLE ONE) level, hilltop, valley, hillside

Driller's License 159 Licensed Driller's Name Sykora Drilling

Depth to Water Bearing Zones (1) 80' ft. (2) 80' ft. (3) 90' ft. (4) ______ ft.

Well Log

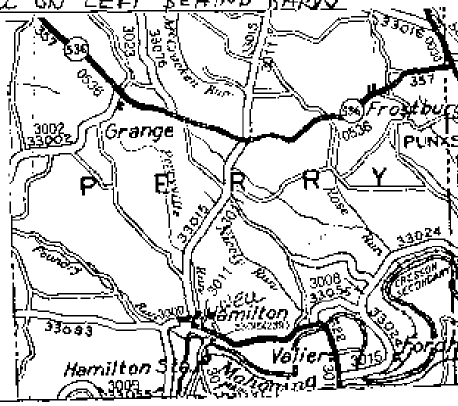
(materials penetrated)	From	To
Clay	0	3
" "	3	37
Sandrock	37	50
Grayshale	50	73
Bottom	73	76
Shale	76	90
Sandrock	90	108
Coal	108	110

Written Well Location Directions RT 536 to Hamilton ~~from Hamilton~~ GO ACROSS BRIDGE WELL ON LEFT BEHIND BARN

Development no ______

Lot ______

SKETCH MA



MAIL 1ST C

...y notable feature such as ...ies/feet).

ER-TGS-15 EV. 6/89

WATER WELL LOG NO. 2

(See Reverse for Explanation)
Department of Conservation and Natural Resources

WATER WELL COMPLETION REPORT
Use Ball Point Pen, Press Firmly and Print Clearly
(DO NOT WRITE IN GRAY COLORED BLOCK)

TOPOGRAPHIC AND GEOLOGIC SURVEY
Water Well Drillers Licensing
PO Box 8453
Harrisburg, PA 17105-8453
717-787-5828

St. 42 Co. ____ Lat. ____ Long ____ Seq: ____ Acc ____
Topo Setting ____ Aquifer ____ Rock Type ____
State Hydrologic Unit ____
Map ____ Well # ____

Well Site

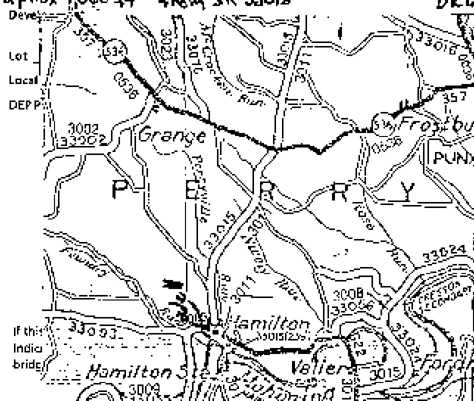
Township/boro/city: Perry
County: JEFFERSON
Address: PO BX 70 HAMILTON PA.
Owner: last name COOK, first name HOWARD
Driller: STOCKDALE (Licensed Name) PA Lic # 1519
Date Drilled: 5-17-02
Well: 119 depth (ft), 6 1/4 dia (in)

Total Casing (1): 66 length (ft), 6 1/4 dia (in); Casing Material: steel / plastic; grouted / not grouted
Total Casing (2): ____ length (ft), ____ dia (in); steel / plastic; grouted / not grouted
Depth to bedrock: 8 ft.
Saltwater zone: ____ ft.
Water-bearing zones: 1) 24 2) 41 3) 105 4) ____
Water levels: ____ ft (static), ____ ft (after test), ____ ft (drawdown)
Yield: 8 gallons per minute (GPM)
Yield Method: bailer, watch/bucket, orifice, est. pump
Length of pump test: ____ hr ____ min

I hereby certify that the above information is true and complete to the best of my knowledge and belief
Smolly Smith 5/20/02
Driller's Signature (Required) Date

(Circle Appropriate Answer)
Well Type: water supply, injection, monitoring, heat pump, test, other ____
Water Use: residence, public, stock, irrigation, institution, industrial, geothermal, other ____
Well Finish: open hole, open end, screen, perforated casing
Length of screen or perforated casing ____ ft.
Drilling method: cable, air rotary, auger, other ____
Landform at site: hilltop, valley, hillside, other ____
Abandoned: No Yes/Why: ____
Written directions to well site: 36s to 536w left on SR 33015 go to Hamilton turn Right on Neal Alley go to the end building aprox 1,000 ft from SR 33015

Devel...
Lot ...
Local...
DEPP...



If th... Indic... bridg... ...s and any notable feature such as quarries, ...)

Well Log

(materials penetrated)	FROM	TO
Bn Clay Fill	0	8
Gr Sandy Shale	8	14
" Sandy clay	14	21
" Sand rock	21	24
" Sandy shale	24	25
" Sand Rock	25	27
" Shale	27	32
" Sandy clay	32	35
" Shale	35	41
" Sand rock	41	45
Dk Gr Shale	45	46
Gr Shale	46	55
" sand rock	55	62
" Sandy shale	62	74
" Shale	74	75
coal	75	77
Gr Clay	77	80
Gr Shale	80	93
" Sand rock	93	95
" Shale	95	112
Gr Sand rock	112	113
" Shale	113	117
Bl Shale	117	119

8700 FM-TGS0015 Rev. 2/97

MAIL ORIGINAL COPY TO THE PENNSYLVANIA GEOLOGICAL SURVEY (REQUIRED)

WATER WELL LOG NO. 3

DEPARTMENT OF CONSERVATION & NATURAL RESOURCES
BUREAU OF TOPOGRAPHIC AND GEOLOGIC SURVEY
WATER WELL LICENSING/WATER WELL INVENTORY SECTION
3240 Schoolhouse Rd
Middletown, PA 17057
717-702-2017

WATER WELL DETAILS

Well Driller: **M & B DRILLING INC**
PA Well ID: **119870**
Driller License: **1398**
Driller Well ID:
Type of Activity: **New Well**
Local Permit #:
Original Well By: **UNKNOWN**
Date Drilled: **10/8/1982**
Drilling Method:

Owner: **HUMBLE RON**
Address of Well:
Zipcode:
County: **JEFFERSON**
Municipality: **PERRY TWP.**
Coordinate Method:
Quadrangle: **VALIER** Latitude: **40.92222** Longitude: **-79.07972**

Well Depth (*ft*): **44**
Well Finish:
Depth to Bedrock (*ft*):
Did Not Encounter Bedrock:
Well Yield (*gpm*): **20**
Yield Measure Method:
Static Water Level: (*ft below land surface*)
Water level after yield test: (*ft below land surface*)
Length of Yield Test: (*minutes*)
Saltwater Zone (*ft*):
Use of Well: **WITHDRAWAL**
Use of Water: **DOMESTIC**

DRILLER'S LOG

UNIT TOP	UNIT BOTTOM	DESCRIPTION OF UNITS PENETRATED

BOREHOLE

CASING

Casing 1:

Top: **0** Bottom: **26** Diameter: **6** Material:

Seal(Grout) 1:

Top: Bottom: Type:

SCREEN/SLOT

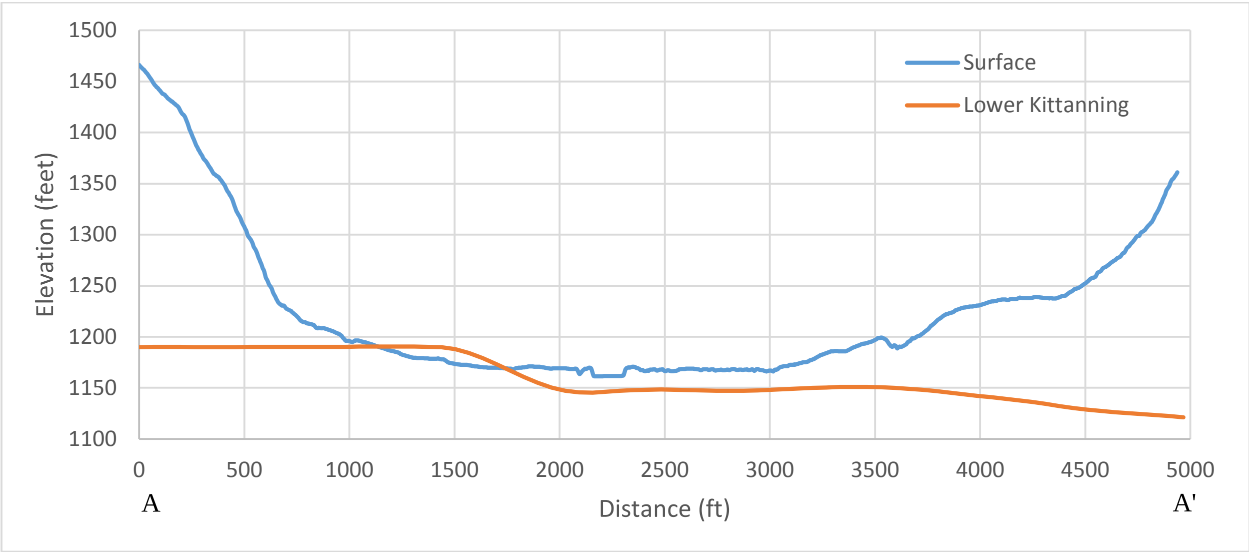
WELL LINER

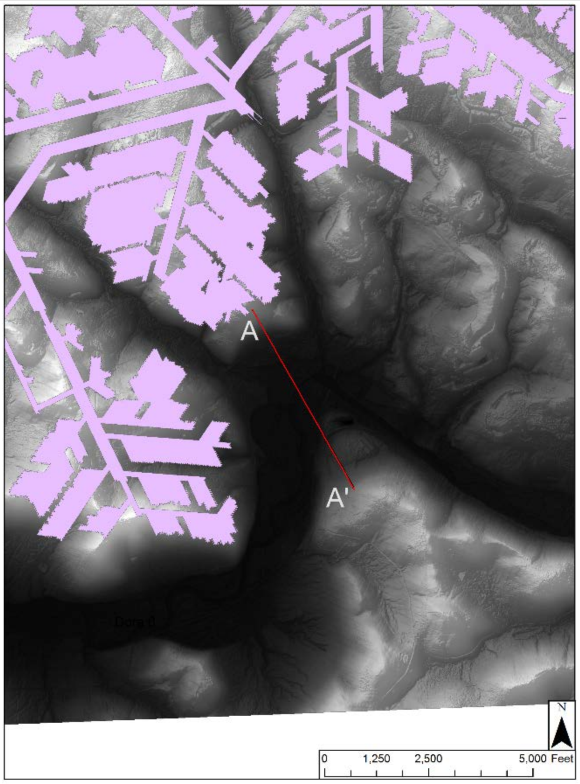
PACKER

WATER BEARING ZONE

Zone 1: Top: **39** Bottom: Yield:

DORA 6 SURFACE AND LOWER KITTANNING PROFILE





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