EVALUATION OF THE LONG TERM IMPACT ON DOMESTIC AND FARM GROUNDWATER SUPPLIES UNDER PENNSYLVANIA LONGWALL MINING CONDITIONS[1]

Timothy D.A. Donohue[2] and Richard R. Parizek[3]

Abstract: Longwall coal mining is a dynamic method of coal extraction that disrupts overlying geologic strata and develops zones of increased permeability. This study was undertaken to determine what long-term effects longwall mining has on overlying domestic and farm water supplies under thick overburden conditions in Pennsylvania. The study region was comprised of the Greene and Washington County area in the southwestern corner of the State where overburden ranges from 700 to 900 ft thick. Investigative methods included analysis of coal company water level monitoring data, interviews with company representatives and State officials, and field contacts with concerned property owners. A new comparative approach for analyzing water level data led to these general conclusions: Hilltop and hillside topographic settings tended to lose water supplies, while valley settings gained new ones in the form of springs and increased water well levels. Deeper drilled wells found in higher topographic settings lost water, while shallower ones in the valley settings remained reasonably unaffected. Three parameters, topographic setting, well depth, and overburden thickness, are recognized as the most important aspects for whether a water supply will be affected by longwall mining under these overburden conditions. Though water supplies were affected by mining, coal companies in the area exhibited good success in finding replacement water supplies by drilling new, deeper wells nearby for those affected property owners.

Additional Key Words: wells, springs, coal mining, control wells, topographic position, overburden thickness

Introduction

The increased use of longwall mining has resulted in a growing opposition as environmental consequences are feared or realized. Objections often cited to longwall mining and its potential adverse environmental influences include (1) land subsidence, (2) the fracturing and differential subsidence of overburden strata that enhances its vertical permeability;, (3) the loss of springs and other shallow groundwater supplies, (4) the capture of surface water by vertical fractures that extend to the land surface, (5) loss of soil moisture relied upon for crop production, (6) changes in surface drainage, (7) undesirable ponding of surface water, (8) damage to utility lines, transportation networks, buildings, etc., (9) releases of methane gas, (10) enhanced acid mine drainage production and other water quality changes, and (11) uncontrolled release of mine water following closure and similar other concerns.

Longwall mining has caused an increase in public concern in coal mining districts throughout the country. This increasing concern has led to, among other things, legislative efforts to regulate and control longwall mining impacts or to eliminate longwall mining entirely. This project was undertaken in response to the emergent need to better understand one aspect of the problem: the hydrogeological impacts of longwall mining in the southwestern portion of the Commonwealth of Pennsylvania. In particular, there is a need to address questions concerning the long-term post-longwall mining impacts on domestic and farm ground water supplies under the complete range of overburden conditions present in various mining districts.

Noteworthy studies that address aspects of the longwall mining in the Eastern U.S. shall include Nutter et al. (1980), Stoner (1983), Cifelli and Rauch (1986), Bruhn (1986), Hiorfdahl (1987), Johnson (1991), Trevits and Matetic (1991), and Leavitt and Gibbens (1992).

Objective

The objective of this project was to develop a method to discriminate between the effects of seasonal weather and droughts on domestic and farm well and spring yields and ground water levels from changes induced by longwall mining. This study was to consider site-specific data under thick overburden conditions in Washington and Greene

[1] Paper presented at the International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage, Pittsburgh, PA, April 24-29, 1994.

[2] Timothy D.A. Donohue, Environmental Scientist, Camp Dresser & McKee Inc., Cambridge, MA, USA.

[3] Richard R. Parizek, Professor of Hydrogeology, The Pennsylvania State Univ., University Park, PA, USA.

Proceedings America Society of Mining and Reclamation, 1994 pp 180-189
DOI: 10.21000/JASMR94040180

https://doi.org/10.21000/JASMR94040180

Counties, PA (fig. 1).

A major portion of this project included analysis of monitoring data made available by three coal companies. All data presented are also contained in mine permit files, which have public access, at the Department of Environmental Resources Office, McMurray, PA with the exception of personal communications.

Geologic and Hydrogeologic Setting of Site Location

Greene and Washington Counties are located in the extreme southwestern corner of Pennsylvania and border West Virginia on two sides. As part of the Appalachian coal basin (Eastern Coal Province), the two-county area, especially Greene County, contains much of the nation's high-volatile bituminous coal reserves. These counties cover a very rugged section of the Allegheny Plateau. Topography of the area is hilly with broad rounded ridges and intervening valleys. Stream erosion has created a complexly dissected area, having as much as 620 ft of relief between hilltops and valley bottoms with almost 90 % of Greene County considered nondevelopable owing to slopes in excess of 15 % (Stoner et al 1987).

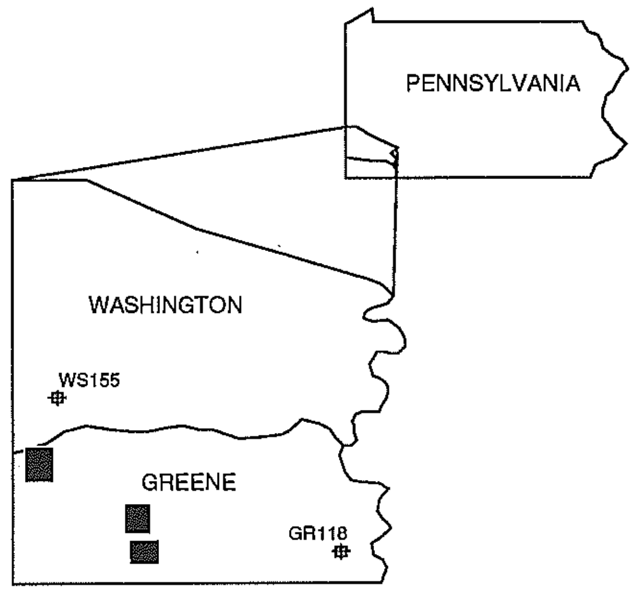

Fig.1 Location of study area, mines, and control wells.

Overburden strata considered for this project consist of stratigraphic units overlying the Pittsburgh coalbed, which is the most valuable coal in the two-county area. It consists of two to four benches separated by clay or shale partings; the lower, or main, bench ranges from 36 to 104 in. in thickness, including clay partings up to 1 in. thick (Stoner et al 1987). Bedrock in the study region consists of interbedded sandstone, siltstone, shale (or mudstone), limestone, and coal. Sandstone and limestone form the thickest lithologic units, exceeding 90 ft in some areas (Stoner 1983). Carbonate units are more prevalent in the lower section of the overburden strata, while sandstone becomes more dominant in the upper portion of the strata.

Water resources for the study area are comprised dominantly of shallow wells and springs. The hydrogeologic characteristics of the overburden strata reflect relatively low hydraulic conductivities and secondary permeabilities in the form of fractures important for sufficient domestic well yields. Fracture flow within bedrock coupled with quaternary alluvium comprises a shallow aquifer system adequate for domestic and farm ground water supplies (Newport, 1973).

Water Well Data Collection

Communication with and cooperation of coal companies in the study area was integral for substantial conclusions to be realized. A random suite of monitoring well sites was selected early in the study from data sets made available by three coal companies. This data acquisition process reduced chance for bias. Owing to time considerations and property owners' fear of jeopardizing their settlements with the coal companies, the study was broken into two parts: analysis of coal company monitoring data, and field contacts made with both company personnel and home owners.

Company data included premining and postmining monitoring records of both wells and springs. In the case of wells, sampling points were either preexisting domestic wells or company-drilled monitoring wells. Data supplied for a property owner's site included water level, yield, and quality before, during, and after longwall mining took place within close vicinity of the well or spring as well as rate of face advance and position of face during mining. Company-drilled monitoring wells provided data during the operational life of each well, which can include data long after mining occurs nearby. This allows for more extensive postmining data to be collected.

Effort was made to contact as many property owners as possible whom would have likely been affected by mining in the study area. Most of the property owners were glad to talk about their situation and about what they may have experienced since mining had occurred in their vicinity but were hesitant about specific documentation of their problem and allowing field measurements. Their concern rested on whether such documentation might in some way jeopardize their situation with the coal companies regarding settlement of claims to repair wells or replace wells and water supplies. Hence, these more general observations and site-specific data are omitted from this report.

Nine wells and 18 springs comprised the monitoring database. An average data set included 2 yrs of monthly measurements for water levels, yields, and quality. Only water level and yield data are considered here. After a database was established, parameters examined for each water resource during analysis included its classification by topographical setting, position of resource above longwall panel, overburden thickness, timing when panel passed and/or undermined, and depth of well.

Preliminary analysis of yield and water level monitoring data indicated that significant fluctuations in static head values occurred when mining was in the vicinity of a well location. However, large fluctuations in precipitation for the area, most noticeably the drought that began in the spring of 1991, also seemed to coincide with head changes. Since all wells in question tapped shallow water-table aquifers, static heads responded to the natural variability of seasonal changes in precipitation and ground water recharge. The problem was finding some way to filter out the effects of variable precipitation from well fluctuations to determine if longwall mining was altering performance of wells. A time series method of analysis was not possible given the limited data set.

The analysis procedure devised, required use of control wells located in areas not impacted by mining or other human influences. Such wells should be constructed similar to local domestic wells which have 15-20 feet of surface casing followed by an open borehole to total depth. They should also have static heads that fluctuate only according to changes in precipitation and natural ground water recharge and discharge. Such wells have been established and are monitored by the U.S. Geological Survey with one well in each county of Pennsylvania. The wells for Greene (GR118) and Washington (WS155) Counties have provided daily static head measurements since the early 1970's (table 1). These control wells were ideal for comparison and proper analysis of on-mine wells. By comparing the static head of the monitoring well with that of the control well for each particular month, it was anticipated that the data would reveal the effect of mining.

Table 1. USGS control well specifications (Water Resources Data - PA).

	USGS Well GR118	USGS Well WS155
Location	Greene County, PA	Washington County, PA
Latitude	39°46'55"	40°02'33"
Longitude..........................	80°01'43"	80°26'13"
Local Site	State Game Land #223	State Game Land #245
Aquifer..............................	Sh & SS of lower member of Waynesburg Formation	Washington Formation
Well characteristics	diam. 6 in, depth 104 ft, cased to 22 ft, open hole.	diam. 6 in, depth 160 ft, cased to 19 ft, open hole

Normalizing Control Well Data

It was necessary to devise an appropriate way of comparing water level responses within control wells remote from longwall mines with those in the monitoring wells located near or above longwall panels. Each control well is shallow, and its water level fluctuates according to water-table aquifer conditions. This compares favorably with water levels within shallow monitor wells located next to longwall panels. Because the control wells are completed in different formations, it is inevitable that each would react somewhat differently according to varying hydrogeological characteristics that dominate ground water occurrence and recharge at a particular site. Therefore, the maximum depth to water or lowest static head of each month for each control well was singled out. The mean of the lowest, monthly static heads for the two control wells was then computed. This allowed for a mean control head value to be determined for each month that represented an average of hydrogeological conditions and maximum fluctuations due to varying precipitation independent of mining. Because the mean control head is based on minimum static heads for each control well, a conservative approach to the effects of mining is taken. This approach allows for a maximum effect of precipitation to be filtered from the monitoring data, hence its conservative stance.

The next step was to combine the static heads of the monitoring wells with those of the mean control. After various attempts, a unique approach was found by plotting the static head of the monitoring well versus a ratio: {static head divided by the control mean value for the corresponding month of sampling}. This was applied for each subsequent month of available water level data up until April 1992, the extent of U.S. Geological Survey data and available monitoring data at time of this writing. By plotting data using this approach, a scatter plot was produced, which in turn was analyzed using a best-fit linear regression approach.

An average slope value of 38 was obtained for the control wells. This allows one to compare monitoring well data for longwall panel hydrogeological settings to this control well value. Logically, a steep decline in monitoring head with little change in the control head will produce a larger ratio, which will transpose into a steeper slope. Therefore, monitoring data plots that have a slope during and after mining that is significantly above 38 are considered to be degradationally affected by mining (fig. 2). Likewise, premining and quite possibly postmining data displays that have slopes below or at 38 are said to be unaffected and quite possibly enhanced by mining.

Analysis of Spring Data

Monitoring data for springs were analyzed using the same control mean technique. Spring yield fluctuations behaved similarly to hydraulic head variations for monitoring and control wells. Using the same graphical analysis, monthly spring yield was plotted versus a ratio of spring yield divided by control mean value for the corresponding month. After applying best-fit lines to the scatter plot, a slope comparison analysis was used to determine which springs were affected by longwall mining. This slope analysis procedure for springs is similar to the well analysis procedure except that the average slope for an unaffected spring is around 35, instead of 38 as described above. As in the well analysis, this technique proved to be extremely useful for filtering out the effects of variations in precipitation on spring yields.

Since changes in slope for spring data are dominated by higher yield changes, it is also helpful to plot spring yield values along with control well data versus the monitoring period to look at transient changes in spring yields. This additional analysis provided further insight into how spring yields varied according to precipitation changes and mining impacts.

Results

Several trends in the monitoring data appeared after applying the control mean method of analysis described above. These data observations reveal that water level responses within some wells and springs were subjected to external forces other than precipitation effects. Longwall coal mining is recognized as the cause of these degradational changes for water levels within domestic and farm wells and springs. No other wells were known to have been drilled nearby that might have caused these well interferences.

Wells

Of the many field variables that were analyzed in determining changes in well performance, three specific ones relate efficiently to data trends: depth of well, topographic position of well, and location of well above panel workings. This is in agreement with observations made by other investigators.

Depth of Well. A clear relationship exists between the depth of a well and the degree to which it is affected by mining. As shown in table 2, shallow wells remain relatively unaffected up to about 50 ft deep. Then, deeper wells show

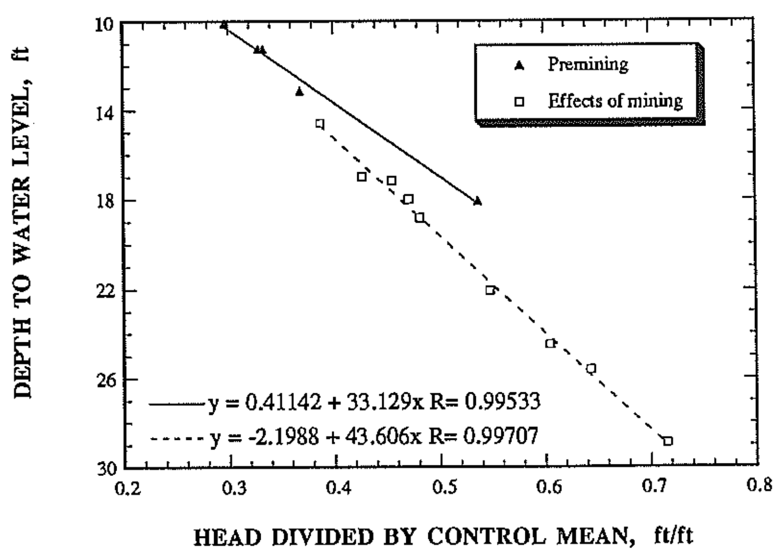

Fig. 2 Control mean evaluation of well 179-W1 affected by longwall mining.

Table 2. Water well construction, topographic setting, location with respect to longwall panel, and response to mining.

Site[1]	Slope of best-fit Premining	Postmining	Impact of mining	Well depth, ft	Topo setting	Elevation, ft	Topo position, ft	Overburden thickness, ft	Position in panel[2]
214-W1	36.33	51.1	Affected	105	hilltop	1324	119	615	ge
88-W1	36.78	41.26	Affected	75	hillside	1038	3	416	219 ft inside
179-W1	33.13	43.61	Affected	62	hillside	1140	-22	549	ge
57-W1	29.12	41.87	Affected	66	valley	1068	42	451	219 ft inside[3]
58-W1	46.6[4]	32.44	Affected	76	hilltop	1141	105	529	188 ft inside[3]
88-W3	NC[5]	45.15	Affected	65	valley	992	-33	440	156 ft inside[3]
56-W1	32.44	NC	Unaffected	50	valley	1017	7	465	344 ft inside
56-W2	39.70	35.61	Unaffected	17	valley	1018	41	498	281 ft inside
88-W2	38.60	39.11	Unaffected	10	valley	996	26	498	125 ft inside

[1] W = well
[2] ge : gate entry inside: located inside mined panel
[3] Located above mined-around block.
[4] High number indicative of mining in adjacent panel.
[5] NC=No change in data trend.

NOTE: all elevations given as feet above sea level.
Casing lengths unknown, generally avg. 20 ft of surface casing.
Topo position = elevation of resource - well depth - base level elevation.
Overburden thickness = elevation of resource - well depth - coal bed elevation.
Base level : elevation of local drainage level.

considerable degradational changes, with the greatest change occurring in the deepest well, 214-W1. A general observation can be made: The deeper a well is, the more likely it is to be affected by longwall coal mining practices. Because most water production is obtained from fracture-borehole intersections, a deeper well is more likely to be affected by increased fracture development in both aquifer and aquiclude strata. Deeper fractures are more likely to be interconnected with mine voids that serve as a free drain. This would cause fractures at the base of the well to act as drains for water cascading into the well from above but that is free to flow out of lower fractures that are interconnected to the underlying mine or mine-subsidence-affected strata. The mine acts as a free drain as long as the mine workings are being dewatered. Fluid potentials in shallow soil and rock are higher than at greater depths as long as the mine subsided strata are being dewatered. Ground water flows toward the mine in response to this head gradient. A drop in fluid potentials is to be expected as monitoring and water supply wells are drilled and cased deeper in the direction of ground water flow. This drop in head will continue until fractures directly interconnected to the mine opening are capable of transmitting ground water into the mine at a rate faster than can be supplied by the overlying aquifers or confining beds. At this stage, the well may be completely dewatered.

There is also a greater chance for borehole restrictions to develop in a deeper well where there is a greater number of fractures present than in a shallow well. Looking at the data displays generated in this study, there is a close relationship between the depth of wells and the topographical position.

Topographical Position of Wells. As with the depth of wells, there is a clear relationship present between the topographical position of a well and the degree of degradation to that well. As seen in table 2, water levels in all of the wells found on hilltops or hillsides were affected to some degree. Levels in valley wells remained relatively unchanged except for well 57-W1. Well 57-W1 is a special circumstance because it is by far the deepest well among those in the valley setting at 66 ft. This depth puts it into the category of deep wells that are affected by mining. Well 57-W1 is also a special case in its location above the panel workings. Generally, a trend exists for hilltop and hillside wells to be degradationally affected by longwall mining and for valley wells to remain essentially unaffected despite special cases.

Location of Well Above Panel Workings. Matetic (1993) and other researchers have conducted detailed studies of water level changes across a profile of a longwall panel to determine changes related to different positions above a panel: gate-entry, one-third inside panel, two-thirds inside panel, and midpanel. This study was limited to data obtained from preexisting wells. Three very interesting observations can be made from data presented in table 2. Well 214-W1 showed the greatest degradational change and is located above a gate entry. Wells 56-W1 and 56-W2 showed no change with possible enhancement in water levels and are located directly above the midpanel. Finally, well 57-W1 is located above a mined-around block of support coal. However, it is located near enough to the edge of the block to be contained within a typical 24° angle of draw. This means that strata below well 57-W1 is in a tensional stress state. Strata surrounding the well at depth have been disrupted, and recharge to the well is affected because mining has occurred around this block. A tensional zone location and loss of recharge combined with its depth of 66 ft would explain its changes despite being located in a valley setting. Of these three interpretations, the fact that wells located above mined-around support blocks are not necessarily free from mining effects is valuable information. This will have a bearing when selecting barrier sizes intended to protect water wells and well fields under a wellhead protection strategy.

Springs

Applying the same control mean method of analysis, springs also show rather similar comparative results to those of wells. However, spring flow data rather than water level elevation data are used in this analysis. Springs are used both as domestic drinking water sources and for farm animal watering troughs in the study area. Springs and wells are both equally important sources of farm and domestic ground water supplies in the two-county study area.

Topographical Position of Spring. Springs primarily occur along hillside locations as well as near hilltops. After examining monitoring data, topographical position in itself is not a clearly defined or independent means of examining trends in spring data as was the case for wells (table 3).

Overburden Thickness. Some springs exhibited different results for the same topographical position, hillside or hilltop. Hence, it was important to examine individual overburden thickness for each spring (table 3). Overburden thickness represents the difference between the topographic elevation of a spring and the Pittsburgh coal seam being mined directly below the water source. Conceptually, the thicker an overburden interval is, the less strata disruption is likely to disturb a spring. Springs 208-S1 and SP-5 are essentially at the same high/topographic elevation, 1,271 ft and 1,300 ft, respectively. However, 208-S1 is affected by mining while SP-5 remains unchanged. A closer examination of their respective overburden thicknesses reveals a clue as to why there is a different reaction to mining in each spring. 208-S1 has an overburden thickness of 670 ft while SP-5 has one of 880 ft. It appears clear from this example that the greater an overburden thickness is for a spring, then the less chance it has of being affected by mining. Obviously, two springs do not comprise a basis for setting standards, but they do help to illustrate the importance of overburden thickness.

Yield Peaks. When analyzing springs for effects of mining, a logical finding would be that a spring went dry or dropped off in yield in comparison to precipitation levels. However, another pattern was noted during spring data analysis and included high yield peaks up to a month prior to having a spring undermined or passed by an adjacent panel (fig. 3). These peaks are considered directly related to mining because plots of spring yields versus control mean head levels over a particular monitoring period show that these yield peaks are not contemporaneous with precipitation increases represented by higher control heads. Though these flow peaks or bursts occur, they are short-lived, and spring yields often drop below premining values following a burst. A yield peak represents a strata disruption and quite likely an increase in hydraulic conductivity of strata surrounding and nourishing a spring. Since the dilation of fractures in strata overlying a spring increases the transmissivity of a perched aquifer, these yield peaks signify a purging of stored water in the aquifer.

Analysis

Two parameters emerge as important quantitative ways to combine data for both spring and well water resources. These were defined after addressing wells and springs individually.

Topographic Position. Topographic position is realized as the elevation of a resource above the drainage elevation or base level for a particular drainage subbasin. This drainage elevation is the elevation of the main stream for a subbasin. A topographic position is represented by the difference between the resource elevation and the respective drainage elevation. Since depth of wells also contributes to whether a well will be affected, topographic position of wells is treated as the difference between the elevation of the bottom of a well and the respective drainage elevation. This analysis provides a quantitative number for the vertical elevation of a resource above the local base or drainage level.

Overburden Thickness. This quantitative analysis is the same method that was introduced in the earlier section for springs. Overburden thickness represents the difference between the resource elevation and the elevation of the Pittsburgh coal seam directly below the resource. As in the topographic position analysis, the overburden thickness for a well is measured from the bottom of the well to the coal seam directly below the resource.

Topographic Position Versus Overburden Thickness. Having determined which monitoring sites were affected or unaffected by mining, a graphical analysis of these sites includes plotting them on a scatter graph with topographic position on the y-axis and overburden thickness on the x-axis. Each point is either an affected or unaffected water resource. There is a clear linear relationship between a resource's position above the drainage plane, its height above the coal seam, and whether it is affected by mining (fig. 4). These two parameters may help to define probability fields for whether a particular water resource will be affected by longwall mining in the Appalachian coal basin. This

Table 3. Location of springs with respect to topographic setting, mine panel location, and observed impact of mining.

Site[1]	Slope of best-fit Premining	Postmining	Impact of mining	Topo setting	Elevation resource, ft	Topo position, ft	Overburden thickness, ft	Position in panel[2]
214-S3	35.35	went dry	Affected	hillside	1350	250	742	313 ft inside
208-S1	34.90	37.47	Affected	hillside	1271	311	670	25 ft inside
214-S4	33.93	32.66	Affected	hillside	1330	230	720	edge
SP-5	35.37	NC[3]	Unaffected	hilltop	1300	200	880	ge
208-S3	35.45	37.51	Affected	hillside	1215	255	613	ge
179-S9	35.33	NC	Unaffected	hillside	1265	165	765	260 ft inside
208-S2	35.04	went dry	Affected	hillside	1190	230	583	94 ft inside
208-S6	34.52	NC	Unaffected	hillside	1232	272	630	ge
179-S10	34.58	NC	Unaffected	hillside	1250	150	756	ge
179-S4	34.86	NC	Unaffected	hillside	1256	156	699	156 ft inside
179-S3	34.41	NC	Unaffected	hillside	1238	138	670	94 ft inside
179-S2	34.78	NC	Unaffected	hillside	1225	125	671	266 ft inside
12-S1	35.16	NC	Unaffected	hilltop	1235	275	810	ge
12-S2	30.05	NC	Unaffected	hilltop	1221	261	796	ge
12-S3	34.25	NC	Unaffected	hilltop	1244	284	819	edge
12-S4	30.00	NC	Unaffected	hilltop	1240	280	815	ge
214-S1	35.53	30.81	Affected	hillside	1206	106	608	313 ft inside
214-S2	35.47	NC	Unaffected	hillside	1200	100	600	47 ft inside

[1] S = Spring

[2] ge : gate entry; inside: located inside mined panel; edge: located on edge of panel

[3] NC=No change in data trend.

NOTES: all elevations given as feet above sea level.
Topo position = elevation of resource - base level elevation.
Overburden thickness = elevation of resource - coal bed elevation.
Base level : elevation of local drainage level.

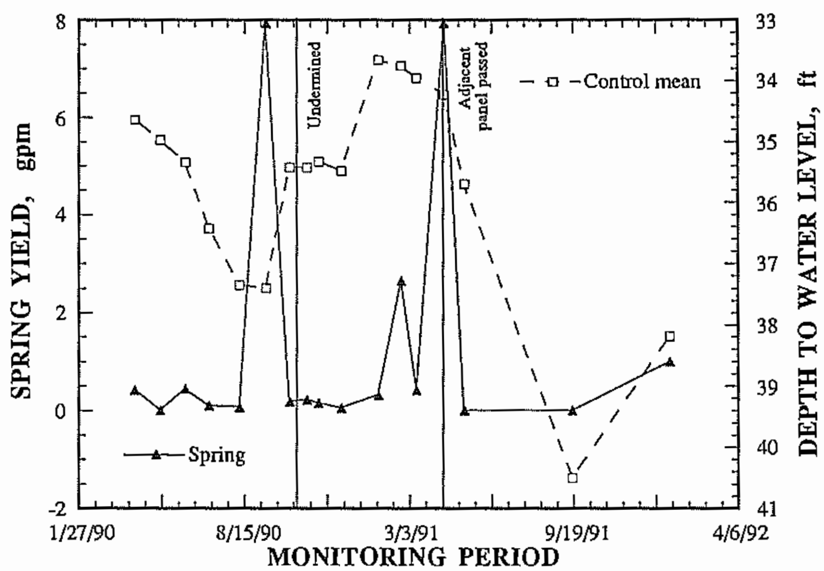

Fig. 3 Graph showing spring yield peaks for 208-S1 along with control mean water levels to evaluate spring response to mining.

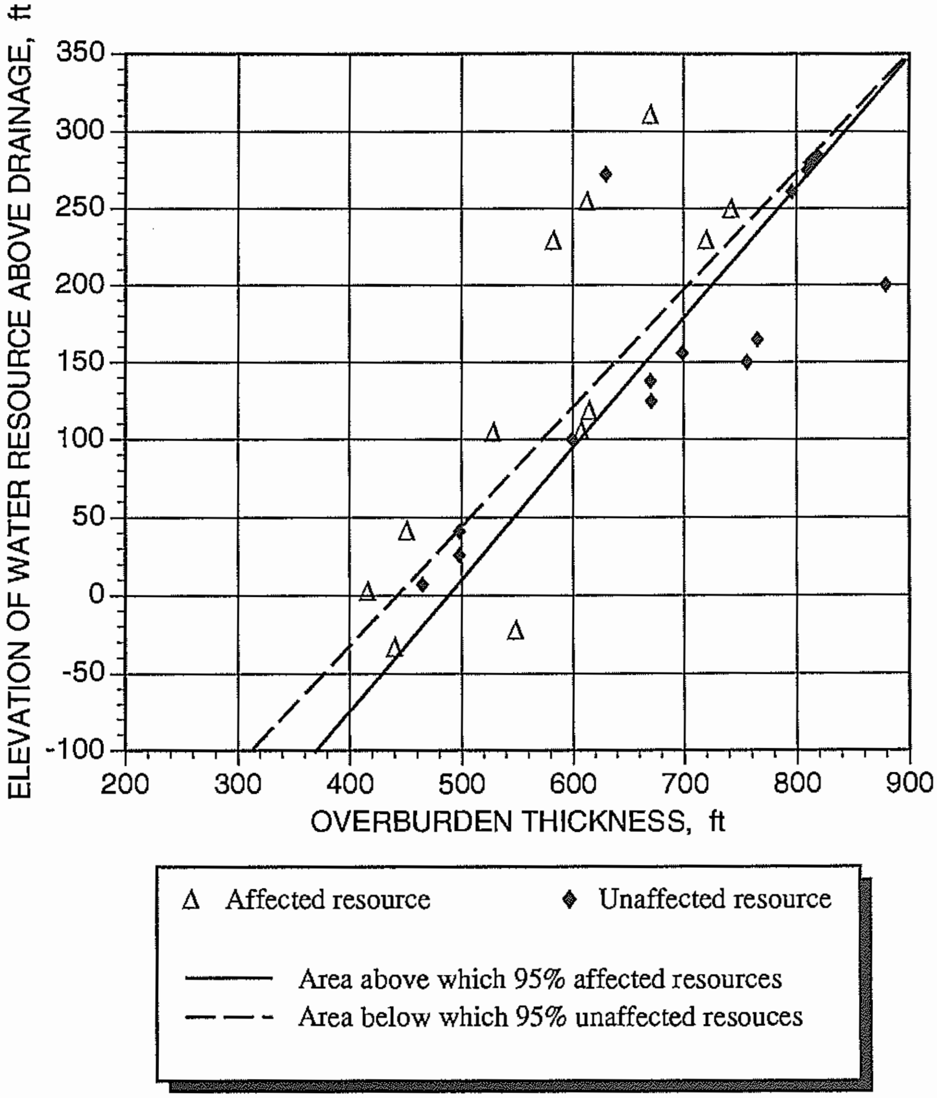

Fig. 10 Resultant graph for affected and unaffected water resources.

relationship applies specifically to the overburden characteristics of the northern portion of the Appalachian coal basin. These results are so encouraging that they warrant further refinement for the full range of overburden conditions expected within various mining districts. As new data are added to figure 4 or its variant to allow for change in topographic relief, overburden rock type, presence of various structural features such as fracture zones, faults etc., it should be possible to assign a water supply failure frequency or risk value to wells and springs likely to be adversely impacted by longwall mining in each hydrogeologic setting. A family of graphs representing various overburden conditions, climate, etc., may be developed. Such graphs would be based upon actual field experience determined on a case-by-case basis and hence should be of value in longwall mine planning, assist in wellhead protection studies, and have similar other uses.

The water level responses of domestic and farm water wells and flow variations of springs influenced by longwall mining under the Greene and Washington County hydrological and longwall mine settings need not be similar to the response observed or expected in other mining districts.

Other Field Observations

General field observations for the effects of mining in this study were in agreement with those of other authors. Property owners located on hilltops and hillsides tended to lose water supplies or saw extreme shifts of their spring locations downslope. Valley bottoms were virtually unaffected in the long run in terms of relocating water. Strata around wells may still shift and cause wells to become inoperable in the valleys, but new wells were very successful in returning reasonable yields to meet replacement water supplies. Conversely, hilltop and hillside topographic and hydrogeologic settings experienced a drop in the water table and hence a migration of springs downslope toward the valley environment. This was prevalent for areas within the mined panel and has been reported by Leavitt and Gibbens (1992) and others.

Conclusions and Recommendations

Longwall coal mining disrupts the hydrogeological regime of overburden strata. However, the degree to which water wells and springs are adversely affected is difficult to discern. After several routes were tried in order to adequately analyze water level data from farm and domestic resources, a new approach in understanding water level changes in wells and spring yields resulting from mining and changing weather conditions was reached. A number of conclusions were drawn:

1. By using two U.S. Geological Survey statewide network and long-term monitoring wells as control wells, a discrete approach to filtering out the effects of precipitation on well changes and spring yields was successful.

2. Deep wells were more likely to be adversely affected by mining than shallow water wells. Wells deeper than 60 to 65 ft fall into this category under the hydrogeologic and mining settings considered for Greene and Washington Counties, PA.

3. Water levels in wells found on hilltops and hillsides were affected in all cases. Water levels in wells found in valleys were essentially unaffected.

4. Location of wells above longwall panel workings did not seem to dominate how wells responded to mining. It was important to note the effects of a typical angle of draw on wells found in a mined-around support block.

5. Overburden thickness plays a significant role as to whether springs are affected by longwall mining.

6. Affected springs exhibit brief yield spikes prior to or during undermining or mining of an adjacent panel. These spikes represent release of water from storage in the shallow aquifers most likely as a result of fracture dilation. As most springs are controlled by rock fractures combined with stratigraphic sequences, slight changes in fracture apertures can be expected to result in a substantial increase in fracture transmissivity as described by the cubic law.

7. Mining causes the local water table to be lowered. This causes a general dewatering of wells located on hilltops and portions of hillsides as well as emergence of springs downslope in valleys. Springs located higher on slopes may show above normal flow during undermining and then often become and remain dry. These findings support those of Booth (1992) and other researchers, who found that subsidence due to longwall mining causes fracturing and dilation of joints, which increases fracture permeabilities and storage coefficients.

8. A linear relationship for affected and unaffected water resources exists between overburden thickness and local topography. These results support Cifelli and Rauch's (1986) findings that given two resources at the same topographic position, the one having a greater overburden thickness will less likely be affected. The same type of reasoning can be employed given two resources with the same overburden thickness but different topographic positions. Leavitt and Gibbens (1992) showed that topographic setting of water resources was the dominant factor governing whether a resource was affected by mining. Both these conclusions are satisfied in this linear relationship for medium-to-thick overburden strata in the Appalachian coal basin. Using these results, a predictive approach could be developed to determine whether a particular water resource will be affected by longwall mining. Further data must be applied to these results to predict the impacts of mining where shallow overburden conditions are present. Also, some variations can be expected when comparing resource data for high, intermediate, and low topographic relief, and for regions with variable overburden stratigraphic sequence, e.g., thick, massive sandstone versus shale, etc.

9. Coal company water supply remediation efforts when supplies are disrupted due to mining seem to be relatively efficient. New wells are often drilled by companies rather than having to deal with cleaning out old wells. In most cases, new, deeper wells are located some 10 ft or so from the old ones and produce yields sufficient for domestic use. Fracture controlled water production allows for this relatively simple reinstallment of lost water supplies.

Acknowledgments

This study was supported by Federal funds from the U.S. Bureau of Mines and The National Mine Land Reclamation Center under Cooperative Agreement CO 388026. Discussions with Gil Mahalich and John Kernic of the McMurray office of the Pennsylvania Department of Environmental Resources were helpful. Personal communication with and cooperation of mining company representatives from three companies using the longwall method were invaluable. They made their maps and files available for use in the study and requested that their names not be included here.

Literature Cited

Booth, C.J. 1992. Hydrogeologic impacts of underground (longwall) mining in the Illinois Basin. p. 222-227. In S.S. Peng (ed.), Proceedings of the Third Workshop on Surface Subsidence Due to Underground Mining. WV Univ.

Bruhn, R. W. 1986. Influence of deep mining on the ground water regime at a mine in northern Appalachia. p. 234-248. In S.S. Peng (ed.), Proceedings of the Second Workshop on Surface Subsidence Due to Underground Mining. WV Univ.

Cifelli, R. C., and H.W. Rauch. 1986. Dewatering effects from selected underground coal mines in north-central West Virginia. p. 249-263. In S.S. Peng (ed.), Proceedings of the Second Workshop on Surface Subsidence Due to Underground Mining. WV Univ.

Hiorfdahl, S.N. 1987. Hydrologic and mining data from an area of underground coal mining in Garrett County, Maryland. Report of Investigations No. 41-A. Dept. of Natural Resources, Maryland Geological Survey in cooperation with U.S. Geol. Survey and the Maryland Bureau of Mines.

Johnson, K.L. 1991. Effects of longwall coal mining on the hydrology of two Appalachian stream valleys. p. 1111-1125. In Proceedings of the Fifth National Outdoor Action Conference, Las Vegas, NV, National Water Well Association.

Leavitt, B.R., and J.F. Gibbens. 1992 Effects of longwall coal mining on rural water supplies and stress-relief fracture flow systems. p. 228-236. In S.S. Peng (ed.), Proceedings of the Third Workshop on Surface Subsidence Due to Underground Mining. WV Univ.

Matetic, R.J. 1993. An assessment of longwall mining-induced changes in the local ground water system. In FOCUS Conference on Eastern Regional Ground Water Issues. September 27-29,1993.

Newport, T.G. 1973. Summary ground water resources of Washington County, PA. 32 p. Pennsylvania Topographic and Geologic Survey, Harrisburg, Fourth Series, Water Resource Report 37.

Nutter, L.J., M.J. Smigaj, and L.L. Knobel. 1980. Basic data report no. 11. Garrett County water-well records, chemical-quality data, groundwater use, coal test-hole data and surface water data. 102 p. U.S. Geol. Survey in cooperation with Garrett County Planning Commission Dept. of Natural Resources, Maryland Geol. Survey.

Stoner, J.D., D.R. Williams, T.F. Buckwalter, J.K. Felbinger, and K.L. Pattison. 1987. Hydrogeology, water resources, and the hydrologic effects of coal mining, Greene County, PA. U.S. Geological Survey, 4th Ser., Water Resources Report, PA Geological Survey.

Stoner, J.D. 1983. Probable hydrologic efffects of subsurface mining. p. 128-138. Ground Water Monitoring Review, Winter.

Trevits, M.A., and R.J. Matetic. 1991. A study of the relationship between saturated zone response and l ongwall Mining-induced ground strain. p. 1101-1109. In Proceedings of the Fifth National Outdoor Action Conference, Las Vegas, NV, National Water Well Association.

Water Resouces Data - PA, Volume 3, Pennsylvania Geological Survey in cooperation with the U.S. Geological Survey.