SESSION 2: MINE HYDROLOGY

Page No.

Shallow Ground Water Flow in Unmined Regions of the Northern Appalachian Plateau: Part 1. Physical Characteristics.
Jay W. Hawkins, Keith B.C. Brady, Scott Barnes, Arthur W. Rose 42

Shallow Groundwater Flow in Unmined Regions of the Northern Appalachian Plateau: Part 2. Geochemical Characteristics.
Keith B.C. Brady, Arthur W. Rose, Jay W. Hawkins, Michael Dimatteo 52

Mine Seepage Problems in Drift Mine Operations.
Clyde DeRossett, David E. Johnson, David B. Bradshaw 63

Effects of Spoil Groundwater on Water-Quality in a Receiving Lake.
Douglas C. Turney, Kenneth B. Edwards, Walter E. Grube, Jr. 72

Ground- and Surface-Water Interactions Involving an Abandoned Underground Coal Mine in Pike County, Indiana.
Denver Harper, Greg A. Olyphant, Donald R. Sjogren 87

Modeling the Effects of Longwall Mining on the Ground Water System.
R.J. Matetic, J. Liu, D. Elsworth 96

Groundwater Conditions Around a Coal-Combustion Residue Site in Southern Illinois.
Steven Esling, Merryn Fielding, Bradley Paul 115

AMERICAN SOCIETY • SURFACE MINING and RECLAMATION •

Shallow Ground Water Flow in Unmined Regions of the Northern Appalachian Plateau: Part 1. Physical Characteristics[1]

by
Jay W. Hawkins, Keith B.C. Brady, Scott Barnes, and Arthur W. Rose[2]

Abstract. At a Pennsylvania study site, ground-water flow and aquifer properties in undisturbed strata are controlled by fracture frequency and aperture development. Analysis of images from a borehole video camera illustrate that the frequency of horizontal and vertical fractures decreases non-linearly with increasing depth. A highly transmissive fractured zone extends from 0 to roughly 15 meters in the strata underlying hilltops and hillsides. This zone exhibited hydraulic conductivities over 100 times higher than strata lying 8 meters or more deeper. These extreme hydraulic conductivity changes permit a temporary perched water table to arise from rainfall events. Surface water quickly enters near-surface fractures and flows rapidly downward and laterally through the shallow fractured zone. Well hydrographs illustrate that the residence time for much of this water is relatively short-- a few days up to a week. Most of this shallow ground-water flow emanates at cropline springs, while most of the remainder continues as shallow ground-water flow and a small portion of the ground water enters the deeper flow system. In the deeper system, the flow rate is substantially slower with a much longer residence time than the shallow zone. This is caused by a low hydraulic conductivity (*i.e.* geometric mean of 1.1×10^{6} m/s). The longer residence time allows the deep-flowing ground water more time to react with the minerals in the strata, increasing conductance and dissolved solids concentrations, relative to the shallow ground water. Specific conductivity profiles in the uncased boreholes illustrate that the conductance of the ground water increases with depth. The increases in conductance observed in some cases were gradual, while in other cases conductance increases were very discrete, corresponding to major fractures intersected by the borehole.

Additional Key Words: Appalachian Plateau, shallow ground-water flow, fracture frequency.

Introduction

The development of stress-relief fractures in undisturbed strata in the Appalachian Plateau has been widely reported (Ferguson, 1967; Ferguson and Hamel, 1981; Wyrick and Borchers, 1981; Wright 1987; Merin, 1989). Stress-relief fractures are created by the removal of rock mass by natural erosional processes. Stress-relief fractures that form in the valley walls are vertical or near-vertical and commonly parallel the valley orientation. Bedding-plane separations and small thrust faults form in the valley bottoms from the compressional stresses.

The frequency and depth extent of stress-relief fractures are directly related to the rock types, degree of induration, rock-layer thickness, and depth. Well indurated units in the valley walls such as thick sandstones and limestones tend to have a lower fracture frequency than less competent shales and claystones (Ferguson, 1967). A study of sandstones revealed a logarithmic increase in distance between fractures and increasing rock-layer thickness (Rats, 1964). Fracture

---

[1]Paper presented at the 1996 Annual Meeting of the American Society for Surface Mining and Reclamation, Knoxville, TN, May 18-23, 1996.

[2]Jay W. Hawkins is a hydrologist with the U.S. Geological Survey (formerly with the U.S. Bureau of Mines) Pittsburgh, PA 15222, Keith B.C. Brady is a hydrogeologist with the PaDEP, Harrisburg, PA 17120, Scott Barnes is a hydrogeologist with the PaDEP, Hawk Run, PA 16840, and Arthur W. Rose is Professor of Geochemistry, Penn State University, State College, PA 16802.

spacing in Appalachia was observed at a fraction of a meter near the surface, increasing to over ten meters at depths up to 90 m (Trainer, 1983). Merin (1989) noted that bedding-plane fracture spacing increased non-linearly with depth, with spacing between fractures ranging from 1.3 cm to over 11 m. He saw no relationship between frequency and increasing depth for most vertical joint sets. Ferguson and Hamel (1981) observed that fractures in competent units tend to terminate at bedding contacts in softer units and that fracturing frequency decreases with increasing distance into the valley walls in the Appalachian Plateau. Borchers and Wyrick (1981), working in southern West Virginia, observed that stress-relief fractures "are a near-surface phenomenon" and that they decrease with depth. They doubted whether these fractures extend below 30 to 60 m. Kipp and Dinger (1987) noted that most fractures were within 46 m of the surface in eastern Kentucky. They reported that highly fractured rock units near the surface were relatively unfractured when more deeply buried beneath ridges. Wright (1987) also observed a significant reduction in fracture frequency and development with increasing depth in southwestern Virginia.

Ground-water flow in strata of the Appalachian Plateau is mainly controlled by the permeability created by stress-relief fractures. Brown and Parizek (1971) observed that sandstones and coals were the highest-yielding aquifers at two sites in central Pennsylvania. Sandstones, coals, and well indurated-units are more transmissive because they are self supporting and can hold fractures open. Softer units (*e.g.*, shales and claystones) are less permeable, because the fracture apertures are narrower (Peffer, 1991). These units are somewhat plastic and self healing; when fractures are created they have relatively small apertures or they tend to close up (Hawkins, 1995).

In a ground-water model developed by Kipp and others (1983), precipitation infiltrates into near-surface open fractures and percolates down until a confining unit is reached. The water then flows horizontally toward the outcrop, where it intersects fractures in the confining unit that allow downward flow, or where it emanates as a cropline spring. The remainder of the ground water continues in a stairstep fashion downward and toward the valley floor. Brown and Parizek (1971) observed a similar flow pattern. They divided the ground-water flow system into three components: 1) an "upper flow system" encompassing topographic highs down to the underground coal mines, 2) a "middle flow system" which discharges laterally and towards the stream valley, and 3) a "lower flow system" that represents the regional ground water system discharging to major river systems. Abate (1993) developed a conceptual ground-water model entailing a series of perched systems above each coal seam at the study site. In this paper, the conceptual ground-water system of this site is expanded and modified using additional testing techniques and data. Previous research and work by the authors at numerous other sites in the Appalachian Plateau indicate that the model developed has widespread applicability.

Site Background

The study site, the Kauffman mine, is located in Boggs Township, Clearfield County, Pennsylvania, midway between the towns of Clearfield and Houtzdale. A map of the site is located in the second part of this paper (Brady and others, 1996). The site is located between Camp Hope Run to the north and Sanbourn Run to the south, within 300 m of the regional drainage system, Clearfield Creek. The site is in a broad upland setting dissected by northwest-flowing tributaries. Topography is fairly steep, with a relief exceeding 200 m above drainage. The soil is relatively thin, sandy, well drained, and rocky. The predominant vegetation are hardwood trees with an undergrowth of ferns and mountain laurel.

Strata of the site and adjacent areas range from Mississippian sandstones at the level of Clearfield Creek to Pennsylvanian siltstones and sandstones forming the hilltops. Mining affects the Middle and Lower Kittanning formations, with the Lower Kittanning No. 2 and No. 3 coals being the target seams. These seams are usually separated by a carbonaceous claystone about 0.5 m thick. Above the No. 3 coal are dark gray to black shales and siltstones. Overlying the dark shales

are gray, thick cross-bedded channel sandstones. In places, these sandstones rest directly on top of the No. 3 seam. About 7.5 m above the No. 3 coal is a thin rider seam, that may be the Lower Kittanning No. 4 coal. Above the rider seam, the strata are predominantly sandstones and siltstones with minor occurrences of clay, shales, and coals. In the western portion of the site, some of the strata within the Lower Kittanning overburden are alkaline. The strata dip slightly (< 2°) toward the west-northwest. Ground water moves primarily through fractures in the rock and cleat in the coal.

At several locations across the site, piezometer nests were installed at 3 or 4 discrete levels. The "A" wells were completed with the 1.5 m screened interval open to the Lower Kittanning coal and enclosing strata. The "B" wells were installed with a 1.5 m screened interval enclosing the Clarion No. 2 coal beneath the Lower Kittanning coal. The "C" wells were completed with a 3 m open interval accessing strata beneath the Clarion coal seam. The "D" wells were left as open uncased boreholes extending down to units slightly below the Lower Kittanning coal with only 3 m of casing extending from the surface through the soil horizon. A few well nests had "E" wells installed in sandstones open at a 1.5 m interval located between the "A" and "B" wells.

Fracture Frequency Analysis

A borehole video camera was used in the uncased boreholes to record and analyze characteristics of the fractures intersected. Fracture frequency, distribution, orientation, and ground-water-yielding fractures were determined from these borehole surveys. Previous research has shown that fracture density decreases with depth (Ferguson and Hamel, 1981; Borchers and Wyrick, 1981; Kipp and Dinger, 1987; Wright, 1987). Studies on the rate of fracturing decrease or fracture orientation are rare. Merin (1989) recorded decreasing bedding-plane fracture frequency and a decrease in hydraulic conductivity with depth in a hard siltstone. Decreasing fracture frequency was reflected by decreases in permeability and significant water-quality differences.

Video tapes of the uncased boreholes were reviewed to determine the fracture orientation and the fracture frequency. The fracture counts were grouped in 10 foot intervals and normalized into fractures per unit length.[1] The first interval started at 10 feet below the surface because casing was installed for hole stability. Fractures were categorized by orientation: 1) vertical/near vertical (90°+/-10°), 2) horizontal/near horizontal, mainly bedding plane separations (0°+/-10°), and 3) oblique, all fractures between vertical/near vertical and horizontal/near horizontal.

The highest fracture frequency intersected by the borehole was observed for horizontal fractures. The relatively high number of horizontal fractures was somewhat unexpected, based on previous research by Ferguson and Hamel (1981) that indicated that bedding-plane separations were more common to the valley bottoms than the ridge tops. Trainer (1983) observed that "bedding-surface openings" are common in horizontally bedded rocks in West Virginia, Maryland, Virginia, and Tennessee. The frequency of horizontal fractures (fig. 1) decreases substantially with depth. The average number of horizontal fractures intersected by the borehole decreases from 0.7 and 0.93 fractures per foot for the 10-20' and 20-30' intervals, respectively, to less than 0.1 fractures per foot at the 100-110' level.

Vertical fractures exhibited the second highest frequency of the three types (see fig. 2). However, given the mode of frequency determination, the number of vertical fractures are probably under-represented spatially in the ridge top. The fractures and boreholes are parallel or nearly so. Therefore, it is anticipated that the number of vertical fractures observed is less than the actual frequency in the strata. Measurements at freshly-exposed highwalls indicate that this assessment is correct. Vertical fractures

---

[1]As an artifact of the borehole videography, the fracture frequency analysis will be reported in english units to maintain consistancy with figures 1 and 2.

frequency significantly decreased at increasing depth. The average number of vertical fractures ranged from 0.77 fractures per foot at the 10-20' interval to none being recorded at the 100-110' interval. Although no fractures were encountered at the 100-110' interval, measurements of hydraulic properties indicate that fracturing extends beyond 100'.

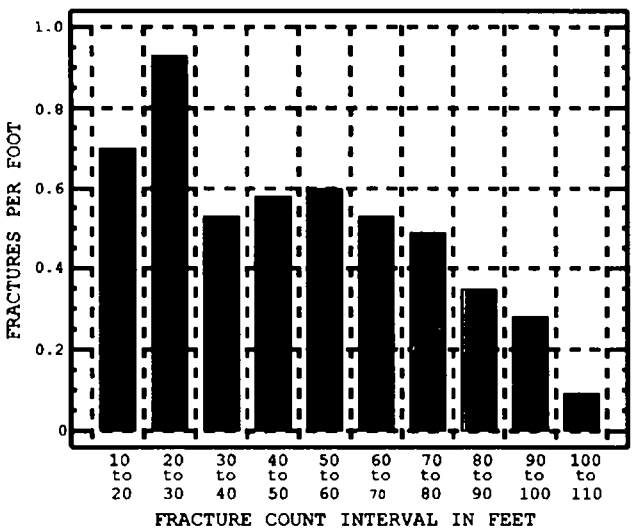


Figure 1. Frequency of horizontal fractures.

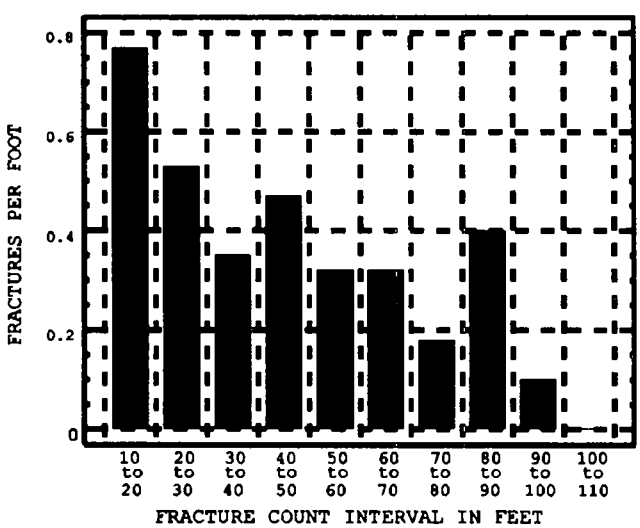


Figure 2. Frequency of vertical fractures.

Oblique fractures exhibited the lowest frequency of the three types. No trends with regard to depth were noted. The lack of frequency changes with depth may be related to the genesis of oblique fractures. The stress-relief origins of most of the horizontal and vertical fractures in the ridge-top wells are directly related to tensile stresses from rock mass removal. Oblique fracture orientation is consistent with those created by compressional forces from past tectonic activity. Compression generated fractures are usually less than 90° and generally 30° on either side of the direction of the compressive force (Billings, 1972). Given the relatively shallow nature of the strata studied (<35 m) and the forces creating oblique fractures, a change in frequency with depth was not expected because tectonic forces are not limited to shallow depths.

Aquifer Properties

Decreasing stress-relief fractures with increasing depth is reflected by lower hydraulic conductivities recorded in the uncased boreholes as the water level decreased. The hydraulic conductivity of several of the uncased boreholes was determined using slug injection tests. The wells were retested several times with differing water levels (saturated thicknesses). The uncased boreholes exhibited a wide range in water levels with fluctuations commonly exceeding 10 m.

Changes in hydraulic conductivity that spanned two orders of magnitude were recorded with water-level fluctuations.[2] With a water-level drop (saturated thickness decrease) of 8 m, from 16.8 m to 24.8 m below the surface, well W6D exhibited a hydraulic conductivity decrease from 3.6×10^{-6} to 3.3×10^{-8} m/s. A similar change was observed in that borehole with a 7.5 m reduction of water level. Well W5D exhibited a decrease in hydraulic conductivity of nearly two orders of magnitude, from 3.1×10^{-7} to 6.0×10^{-9} m/s, with a 8 m water-level drop, 10.8 m to 18.6 m. Well W22D exhibited a change in hydraulic conductivity from 4.6×10^{-6} to 1.3×10^{-7} m/s with a water level decrease of 3.8 m. Testing of well W7D showed a substantial and systematic reduction in hydraulic conductivity with minor water-level drops. With a water level of 21.55 m,

[2]Complete hydraulic conductivity and transmissivity data for this site are available upon request.

22.24 m, and 22.61 m below the surface in W7D, the estimated hydraulic conductivity was 2.3 X 10^{7}, 1.3 x 10^{8}, and 5.1 x 10^{9} m/s, respectively. Merin (1989) observed similar hydraulic conductivity decreases with depth in a siltstone aquifer of the northern Appalachian Plateau.

The remaining uncased boreholes (W2D, W3D, and W4D) exhibited relatively small water-level changes (<3 m) when they were tested. Hydraulic conductivity changes for these wells and wells W5D, W6D and W22D, with minor water level changes, were small (<10X).

In contrast to the uncased boreholes, aquifer testing of the piezometers by both slug injection and constant discharge yielded no distinct trends with regard to increasing depth. The hydraulic conductivity ranged from 10^{6} to 10^{7} m/s. The lack of trends may be due to the relatively narrow open interval (1.5 m or 3 m). The piezometers access the deepest levels or below the levels of the uncased boreholes. Fractures at depth are of a hit-or-miss nature. Short intervals (<5 m) with very few or no visible fractures were commonly observed in the boreholes. This was especially true for the deeper rock units. Therefore, the hydraulic conductivity of the piezometers may exhibit large deviations from the average conductivity, mainly toward lower values.

Well Hydrographs

The substantial hydraulic-conductivity decreases observed with depth create a temporary shallow perched system following significant precipitation events. Hydrographs for the uncased boreholes and water-level measurements in the piezometers indicate that precipitation events create a bimodal flow system in the uppermost unconfined aquifer. A shallow perched flow system develops above the water table, causing water levels in the uncased boreholes to rapidly rise. The deeper water table continues to exist in the "core" of the hill above the underclay of the Lower Kittanning coal. The piezometers did not exhibit similar rapid water-level changes. Tighter strata within the deeper system cause ground-water flow to be much slower, with longer retention times than the shallow zone. Recharge to this lower zone has a longer lag time than the shallow zone.

With precipitation, water rapidly infiltrates into near-surface fractures. Ground water flows vertically for several meters (roughly 7 to 17 m) and then flows laterally toward the hillsides. Depth to which the water will percolate until it begins to flow laterally depends on the hydraulic conductivity, which is directly dependent on fracture aperture size and frequency. Aquifer testing illustrates that large changes in hydraulic conductivity (>100X) can occur within a short distance (8 m) vertically. This magnitude of hydraulic conductivity change is often defined as the distinction between an aquifer and an aquitard. These hydraulic conductivity changes with depth cause the formation of a temporary shallow perched water table. Water from this shallow system rapidly enters the uncased boreholes and fills them to the level of the upper saturated surface (see figs 3) and 4). The rate of inflowing water from shallow depths is greater than the rate the water is reintroduced into the lower and less permeable strata. The subsequent return of water levels to pre-rainfall levels are regulated by the hydraulic conductivity of the lower units and the low inflow rate that continues for several days to a few weeks after a precipitation event. Similar temporary perched ground-water systems have been observed at numerous other sites in the northern Appalachian Plateau (*e.g.*, Garrett Co., Maryland; Westmoreland Co., Pennsylvania) (Hawkins, unpublished data).

The boreholes exhibited water-level rises exceeding 12 meters from the onset of rain. Commonly, the initial water-level rise was observed 5 to 20 hours after the start of rain, whereas the peak usually occurred in less than 30 hours for well W5D and 48 hours for well W6D. This compares to 25 hours for the initial rise and 120 hours for peak rise for a cropline spring located on the site (Abate, 1993). The longer response time for cropline springs is caused by the longer vertical and lateral flow distance. Figures 3 and 4 are examples of water-level responses to rainfall events of 2.92 cm over 12.5 hour and 7.44 cm over 22 hour periods, respectively. These rapid water-level increases, if no additional rainfall

occurs, are followed by a much slower return to pre-rainfall levels (Fig. 4). The protracted return to pre-rainfall levels is regulated by the permeability of the lower sections of the boreholes. Piezometers accessing the same units as the lower sections of the open boreholes do not exhibit the same rapid water-level rise as the boreholes. The water levels in the boreholes were over exceeding 15 meters above levels measured concurrently in comparable piezometers. A much longer time interval is required with recharge to this lower zone.

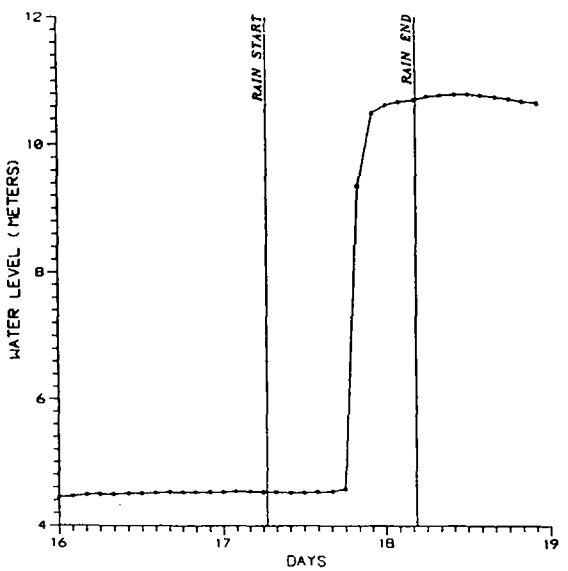


Figure 3. Hydrograph of well W6D from August 16 to 19, 1994.

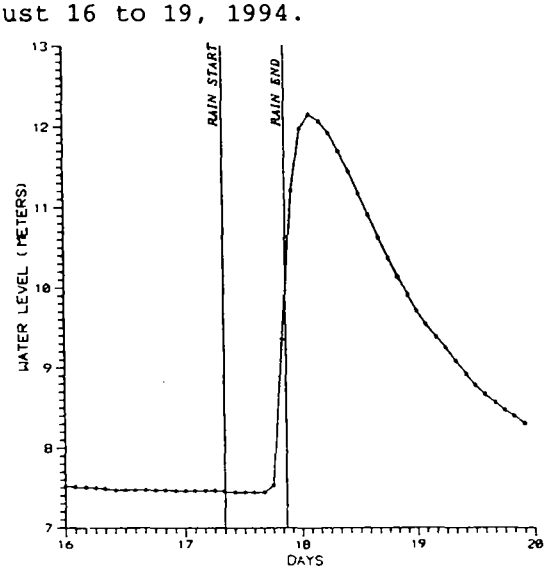


Figure 4. Hydrograph of well W5D from September 16 to 20, 1994.

Most of the ground water in the shallow perched zone, upon reaching the less fractured and unweathered zone, will rapidly flow laterally along a path nearly parallel to the surface. When a unit is encountered with poorly developed fractures, (*e.g.*, coal underclay), much of this water will emanate as a cropline spring. Figure 5 is a schematic cross-section, conceptually illustrating the shallow ground water flow. This water has a relatively short in-ground residence time and flows primarily through highly-leached strata. Therefore, the spring water exhibits a very low ionic strength, similar to rainwater. The chemical quality aspects of this water are discussed by Brady and others (1996).

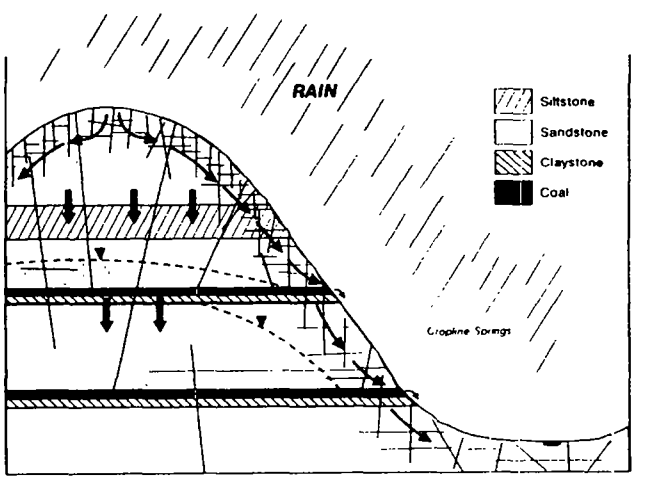


Figure 5. Schematic cross-section with conceptual ground-water flow paths.

The vertical hydraulic conductivity changes observed are not as abrupt as those associated with lithologic changes; they occur over a moderate distance. Therefore, a small amount of ground water flow continues in the shallow zone for several weeks after precipitation. A low-rate seepage was commonly observed into the open boreholes (at this site as well as several other sites in the northern Appalachian Plateau) several weeks following the last rainfall. This small amount of ground-water flow is what maintains the flow at the springs

through dry periods. The gradual reduction of vertical and horizontal permeability in the shallow fractured zone permits continued ground-water flow long after the last rainfall event. Small aquitards or less permeable areas within the shallow fractured zone may also be a source of this slow-release water. Spring-water quality during dry periods indicates that the majority of the water originates in the shallow fractured zone, rather than in the deeper ground water system (Brady and others 1996).

Conductivity Logs

The short residence time of the shallow perched system and the longer residence time of the deeper unconfined system is reflected in the water quality observed in the uncased boreholes. Logging recorded increases in specific conductance with increasing depth in the uncased boreholes.

Some of the boreholes or portions of boreholes exhibited a relatively gradual increase with increasing depth. Figure 6 illustrates a gradual specific-conductance increase from 11 to 18 m and 19 to 30 m below the surface. Other boreholes exhibited substantial conductivity rises in a short distance (0.3-1.0 m). Figure 6 exhibits one of these rapid rises between the 18 and 19 m levels. A series of these conductivity jumps are exhibited by figure 7 at 20, 28, 31, and 32 m below the surface. The video logs show that these conductivity increases correspond to the locations of prominent fractures intersected by the borehole.

Not all fractures observed in the boreholes caused conductivity increases. There were numerous prominent fractures intersected by the boreholes that did not correspond to conductivity increases. However, the conductivity increases were always associated with fractured zones. This indicates that not all fractures contribute to the ground-water flow system. Booth (1988) observed that individual fractures may represent discrete aquifer zones that may have a distinctly different piezometric surfaces. Rasmuson and Neretnieks (1986) estimated that 5-20 percent of the fracture plane carries 90 percent of the water. Ground water flows through "channels" within fracture planes. Where fractures do not have corresponding conductance increases, ground water in these fractures may be of similar quality to water in fractures located above, or this may be where water from the borehole re-enters the aquifer. The latter is especially true in the lower portions of the hole, but may also occur in higher fractures during substantial recharge periods. When the head in the borehole exceeds the pressure head of a fracture, inflow from the borehole to the aquifer will occur.

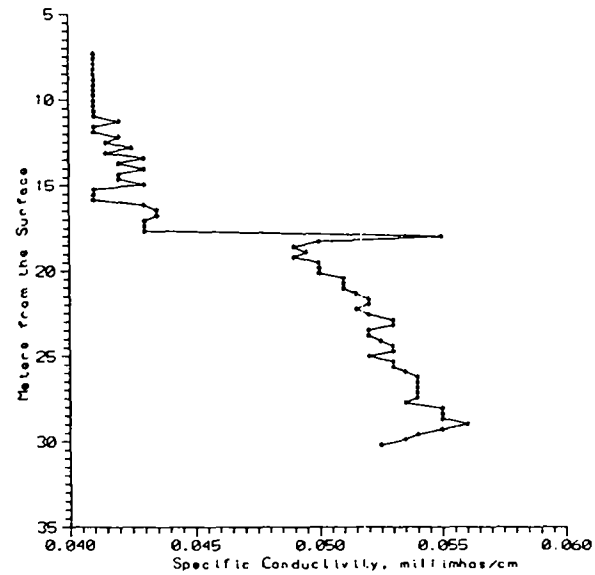


Figure 6. Specific conductance log for well W4D.

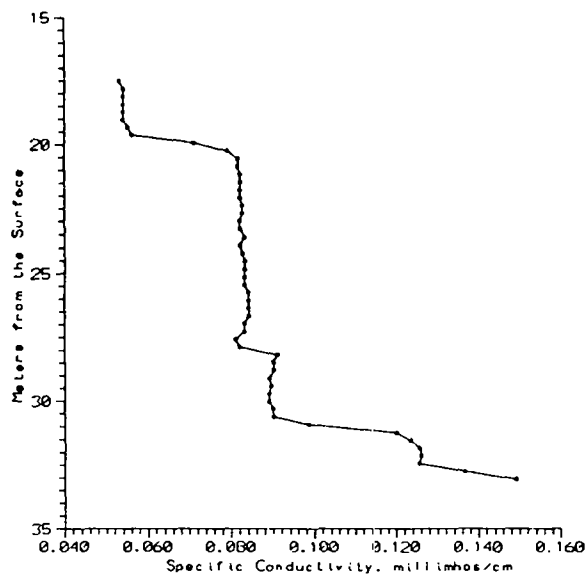


Figure 7. Specific conductance log for well W6D.

Piezometer Data

Head levels measured in the piezometers indicate that there is a downward flow component for ground water across the site. Head potential decreases between piezometers within a nest ranged from 0.23 to 1.0 m for each meter of increasing depth. Decreasing water levels indicate that the ridge top is a recharge area. The water levels measured in the "D" wells represent a composite of the different head levels of the rock units accessed.

Water levels exhibited by the piezometers indicate that a series of confined or semi-confined aquifers exist below the unconfined aquifer above the Lower Kittanning coal. Piezometric surfaces exhibited by "C" wells were above the level accessed by the "B" wells, but below their piezometric level. Abate (1993) suggested that "non-uniform pressure distribution" and substantial vertical head reduction below coal underclay units indicated that a series of perched aquifers exist near the outcrop. These aquifers above the regional aquifer probably exhibit both confined and unconfined conditions depending on the location monitored within the site (*e.g.*, unconfined near the outcrop). Specific portions of an aquifer may also exhibit confined and unconfined conditions at different time periods.

Discussion and Conclusions

Based on the data and information presented, a refined conceptual ground-water model has been created. An extensive review of the published literature indicates that this model is applicable for fractured sedimentary strata throughout most of the Appalachian Plateau. Minor modifications may be required in some regions.

A highly fractured and weathered zone up to 20 meters thick blankets the hilltops and hillsides in the Appalachian Plateau. This zone is highly transmissive and is underlain by progressively less transmissive fractured units. This less transmissive zone facilitates a temporary perched system from rainfall events. Rainwater quickly infiltrates into near-surface fractures flowing vertically for a several meters and then flows laterally toward the hillsides. This water has a short residence time in this shallow, highly transmissive zone. Much of the laterally flowing near-surface ground water emanates at cropline springs. These springs occur at the level of the coal seams. Fractures in the coal underclay tend to be poorly transmissive. Some shallow flowing water passes through the underclay and continues down slope in the weathered/highly fractured zone. Some of this shallow-flowing ground water recharges underlying aquifers via deeper fractures and emanates from coal seams at lower elevations. This conceptual ground-water flow system is illustrated by figure 5.

The short residence time (days to a week) for most of the shallow-flowing ground water is reflected by the low ionic strength of water at cropline springs. Ground-water quality is reported in detail in the second part of this study (Brady and others, 1996).

Data collected from the piezometers indicates that a series of confined or semi-confined aquifers exist beneath the water-table aquifer underlying a coal underclay. Decreasing head levels with depth indicate that there is a downward ground-water flow component. Aquifer tests performed on piezometers in the deeper confined aquifers illustrate that they have low transmissive properties and moderate head pressure; therefore, ground water movement into them and through them is slow. Decreases in the fracture frequency with depth account for the reduction in hydraulic conductivity with depth in the unconfined aquifer and the low hydraulic conductivity of the underlying confined units.

Determination of ground-water flow in the Appalachian Plateau is complex. Changes in transmissive properties caused by decreasing fracture development with increasing depth must be considered when designing a monitoring and water-quality characterization plan. Water quality at cropline springs is representative of ground water flowing through a near-surface, highly fractured and weathered zone. Monitoring wells installed into the core of the hill access ground water that reflects the deeper and slower moving aquifer systems. Deep ground-water quality is indicative of

the geochemical quality of the deeper strata. Below the unconfined zone, a series of confined aquifers exist with a continued downward ground water flow component.

A comprehensive literature review and the widespread experience of the authors indicate that the conceptual ground-water model developed in this paper is applicable to fractured strata aquifers throughout the Appalachian Plateau. However, in certain regions, minor adjustments may be required to completely characterize the system.

Acknowledgments

The authors wish to acknowledge Christopher Abate for the initial research that was conducted on this site. We want to thank all the personnel of Al Hamilton Contracting that aided with the project and have tolerated our frequent occupation of the operation. The authors also wish to thank the reviewers. This research was conducted and funded by the U.S. Bureau of Mines.

Literature Cited

Abate, C. 1993. A Numerical Modeling Approach to Estimation of Parameters Describing Groundwater Flow in Coal-Bearing Rocks of the Allegheny Plateau. Unpublished Doctoral Thesis, The Pennsylvania University, Dept. of Geosciences, University Park, PA, pp. 144.

Billings, M.P. 1972. Structural Geology, 3rd ed., Prentice-Hall, Inc. Englewood Cliffs, New Jersey, 606 p.

Borchers, J.W. and G.G. Wyrick, 1981. Application of Stress-Relief-Fracturing Concepts for Monitoring the Effects of Surface Mining on Groundwater in Appalachian Plateau Valleys. Proceedings of Symposium on Surface Mining Hydrology, Sedimentology and Reclamation, Lexington, KY, pp. 443-449.

Brady, K.B.C., A.W. Rose, J.W. Hawkins, S. Barnes, and M.R. DiMatteo, 1996. Shallow Ground Water Flow in Unmined Regions of the Northern Appalachian Plateau: Part 2. Geochemical Characteristics, Proceedings of the Symposium on Mining Hydrology, Sedimentology, and Reclamation. Lexington KY.

Brown, R.L. and R.R. Parizek. 1971. Shallow Ground Water Flow Systems beneath Strip and Deep Coal Mines at Two Sites, Clearfield County, Pennsylvania. The Pennsylvania State Univ., University Park. Special Report of Research SR-84. 207 pp.

Ferguson, H.F., 1967. Valley Stress Release in the Allegheny Plateau. Engineering Geology, Vol. 4., No. 1. pp. 63-71.

Ferguson, H.F. and J.V. Hamel, 1981. Valley Stress Relief in Flat-lying Sedimentary Rocks. Proceedings of the International Symposium on Weak Rock, Tokyo, Japan, pp. 1235-1240.

Hawkins, J.W., 1995. Impacts on Ground Water Hydrology from Surface Coal Mining in Northern Appalachia. In proceedings of Water Resources at Risk, American Institute of Hydrology, Denver, CO, pp. IMWA-32-IMWA-43.

Kipp, J.A. and J.S. Dinger, 1987. Stress-Relief Fracture Control of Ground-Water Movement in the Appalachian Plateaus. In Proceedings of the Focus on Eastern Regional Ground Water Issues: A Conference, Burlington, VT, pp. 423-438.

Kipp, J.A., F.W. Lawrence, and J.S. Dinger, 1983. A Conceptual Model of Ground-Water Flow in the Eastern Kentucky Coal Field, In proceedings of the 1983 Symposium on Surface Mining, Hydrology, Sedimentology and Reclamation, Lexington, KY, pp. 543-548.

Merin, I.S., 1989. Characterization of Fractures in Devonian Siltstone, Northern Appalachian Plateau: Implications for Ground Water Flow. Proceedings of the Third National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, NWWA, Dublin OH, pp. 921-934.

Peffer, J.R., 1991. Complex Aquifer-Aquitard Relationships at an Appalachian Plateau Site. GROUND WATER, Vol. 29, No. 2. pp. 209-217.

Rasmuson, A. and I. Neretnieks, 1986. Radionuclide Transport in Fast Channels in Crystalline Rock. Water Resources Research, Vol. 22, No. 8, pp. 1247-1256.

Rats, M.V. 1964. Relation of Fracture Spacing to Thickness of Layer. A.G.I. translation from the Doklady Academy of Sciences of the U.S.S.R. pp. 63-65.

Trainer, F.W., 1983. Some Perspectives on Near-Surface Fractured-Rock Aquifers, Proceedings of the Fourteenth Biennial Conference on Ground Water, California Water Resources Center, Report No. 56. Sacramento, CA, pp. 104-122.

Wright, W.G., 1987. Hydrologic Factors Affecting Flow in the Ground-Water System of the Coalfields of Southwestern Virginia. In Proceedings Symposium on Mining Hydrology, Sedimentology, and Reclamation. Lexington KY. pp. 419-422.

SHALLOW GROUNDWATER FLOW IN UNMINED REGIONS OF THE NORTHERN APPALACHIAN PLATEAU: PART 2. GEOCHEMICAL CHARACTERISTICS[1]

Keith B.C. Brady, Arthur W. Rose, Jay W. Hawkins,
and Michael R. DiMatteo[2]

ABSTRACT. Surface mines in Pennsylvania occur in the shallow (< 60 m depth) groundwater flow system and typically are located in groundwater recharge areas. Two shallow flow systems are usually present in unmined areas: an upper weathered-rock zone and a deeper unweathered-rock zone. The weathered-rock zone, although variable, is commonly 6 to 12 m thick. Groundwater in the weathered-rock flow system, as evidenced by shallow wells and cropline springs, has low dissolved solids (specific conductance < 50 μS/cm). The deeper unweathered-rock flow system, as evidenced by water from wells deeper than 10 m, has higher concentrations of dissolved constituents. The differences in water quality are due to previous intensive leaching of minerals within the weathered-rock zone and to much higher flow rates in the more porous and fractured weathered zone. In particular, calcareous minerals are absent or negligible in the weathered-rock zone, but can be appreciable in the unweathered-rock zone. This distribution of calcareous minerals, groundwater contact time with rock, and flow path influence the groundwater composition and concentrations of dissolved ions. A positive relationship exists between the presence and abundance of calcareous minerals and associated groundwater alkalinity.

Our observations are probably applicable to much of the Appalachian Plateau. Groundwater alkalinity can help determine the presence and distribution of calcareous minerals within coal overburden. Coal-cropline springs should not be depended upon for showing groundwater quality associated with the coal seam; they typically only reflect shallow flow through weathered rock. Deeper wells are required to determine the chemical characteristics of water in the unweathered rock zone.

Additional Key Words: groundwater chemistry, acid-base accounting, weathering, groundwater flow

Introduction

The companion paper (Hawkins et al., 1996, this proceedings) provides a review of groundwater hydrology studies on the plateau. This paper addresses chemical evidence in support of that model. Our model defines two separate shallow groundwater flow systems in unmined areas within the unglaciated portions of the Appalachian Plateau of western Pennsylvania. Numerous studies throughout the plateau, from Kentucky to New York have examined shallow groundwater hydrologic characteristics, but few have related water chemistry to the groundwater hydrology.

The three areas discussed in this paper lie within the Allegheny Mountain section of the Appalachian Plateau physiographic province. This portion of the plateau has moderate to high relief (90 to 300 m), marked by deep, V-shaped valleys (Berg et al., 1989). Stratigraphically the sites occur within the Pennsylvanian Period middle Allegheny Group (Sites A and B) and upper Allegheny Group/lower Glenshaw Formation (Site C). Structurally the rocks are horizontal to gently dipping (generally < 6°).

Natural water quality in shallow groundwater flow systems of the Appalachian Plateau results primarily from the influence of three factors: (1) the chemistry/mineralogy of the rock that the water contacts, (2) flow path, and (3) water and rock contact time. Although many solutes are present, we concentrate on bicarbonate alkalinity, because it can be compared to overburden neutralization potential (NP) (an estimation of calcareous mineral content) and because it can be used as a mine drainage quality prediction tool. Other water quality parameters will be addressed where appropriate.

[1]Paper presented at the 13th Annual National Meeting of the American Society for Surface Mining and Reclamation, May 18-23, 1996.

[2]Keith B.C. Brady and Michael R. DiMatteo, Hydrogeologists, Dept. of Environmental Protection, Harrisburg, PA 17105; Arthur W. Rose, Professor, Dept. of Geosciences, Penn State Univ., University Park, PA 16802; Jay W. Hawkins, Hydrologist, USGS (formerly with US Bur. of Mines), Pittsburgh, PA 15222.

Shallow groundwater is associated with two distinct flow-systems. The one system, represented by coal-cropline springs, is recharged from the near-surface zone of weathered rock up slope from the spring. This zone consists of soil, colluvium (in some areas), and weathered and highly fractured rock. This weathering is both chemical and physical. The weathering is enhanced by stress-relief fracturing on the hill slopes and by bedding plane separations, which promote intensified chemical weathering and resulting porosity increases (Hawkins et al., 1996). The weathered zone, as seen in strip mines and drill logs, is typically 6 to 12 m thick, but can extend deeper along fractures. The weathered zone is typically devoid of calcareous minerals and pyrite (Singh et al., 1982; Brady et al., 1988). It is characterized by a yellow-red-brown color resulting from iron oxidation. The lower boundary of the weathered zone is an irregular surface. The irregularity is caused by variations in fractures, topography and lithology.

The other flow-system is below the weathered rock within the zone of largely unweathered bedrock. The unweathered bedrock zone is much less fractured, having fewer bedding plane separations and stress-relief fractures. The bedrock zone retains calcareous minerals and pyrite (if originally present) and the rocks are typically gray, with iron oxidation restricted to some fractures and bedding plane separations.

Most water flowing through the weathered zone has a relatively short residence time (days to weeks) because of the shallow nature of this material and higher permeability which is induced by the factors cited above. Some storage is present, however, because the springs continue to flow during dry periods. The absence of readily leachable or oxidizable minerals and the short residence time results in spring-water quality which typically has low concentrations of dissolved ions.

The water flowing through the unweathered-rock zone has longer residence time (months to years) because of lower permeabilities (Hawkins et al., 1996) and the slower flow rate allows longer contact with soluble minerals. Groundwater in unweathered rock typically has greater concentrations of dissolved solids than water emanating from weathered regolith. Water chemistry from unmined areas can provide information concerning the groundwater flow system.

Methods

The three study areas discussed in this paper were selected because they had: (1) water chemistry data from coal-cropline springs, (2) water quality from wells completed down to the same coal seam as the cropline springs, and (3) acid-base accounting (ABA) data.

ABA is defined by two parameters, neutralization potential (NP), which is an approximation of calcareous mineral content (reported in terms of parts per thousand $CaCO_3$; traditionally reported as tons $CaCO_3$/1000 tons of material), and maximum potential acidity (MPA), which is an approximation of pyrite content. MPA is converted to the same units as NP by multiplication of the weight percent total sulfur by the stoichiometric equivalence factor of 31.25 (Cravotta et al., 1990). Average NP's and MPA's were determined for each overburden drill-hole by using thickness weighting and assuming each hole represented a column of constant diameter, following the methods described in Smith and Brady (1990).

All water quality sample locations were represented by multiple samples. Medians were determined for pH. Other water quality parameters discussed in this paper, unless specified otherwise, are mean concentrations.

Mine Sites

To illustrate the relationship between rock chemistry and water chemistry, several specific examples will be given. All sites discussed are isolated hill tops where the only recharge is from direct precipitation. In all cases the coal outcrops along the sides of the hill, and cropline-springs and bedrock monitoring wells are present.

MINE A: Boggs Township, Clearfield County

Mine A is the Kauffman mine where various research studies have been and are being conducted (see Abate, 1993; Evans, 1994; Rose et al., 1995; Hawkins et al., 1996, this volume). Mine-site topography, locations of drill holes and water-sample points for this mine are shown on Figure 1. This map also shows alkalinity and specific conductivity of wells and springs associated with the lower Kittanning (LK) coal seam, plus a few springs flowing from the Clarion #2 cropline. All the wells are completed as 10-cm-diameter piezometers that are open for 1.5 m at the interval of the LK coal. Figure 1 also

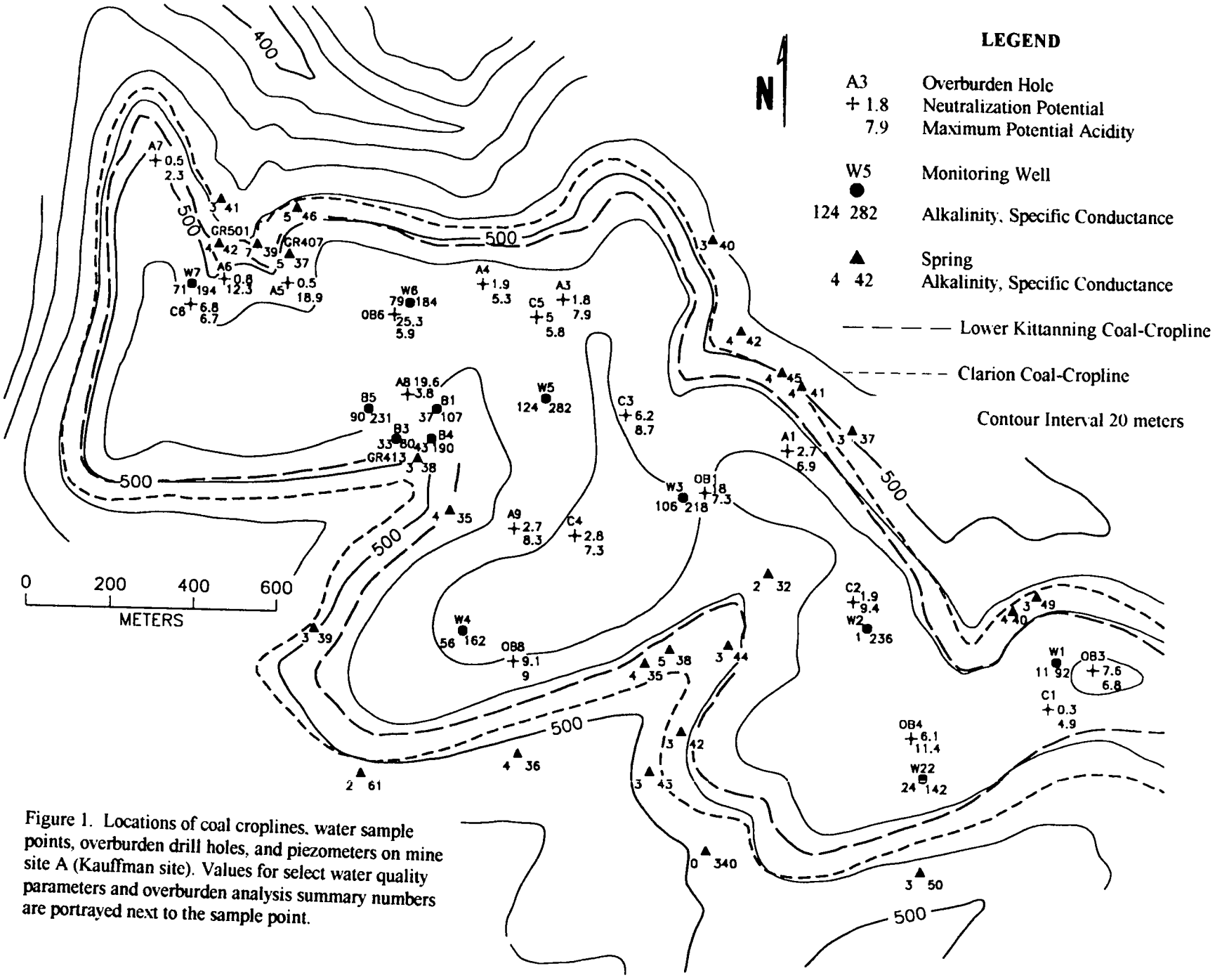


Figure 1. Locations of coal croplines, water sample points, overburden drill holes, and piezometers on mine site A (Kauffman site). Values for select water quality parameters and overburden analysis summary numbers are portrayed next to the sample point.

shows summaries of acid-base accounting data for overburden drill holes.

Figure 1 clearly indicates that spring-water quality is significantly lower in alkalinity and specific conductance than well water. Alkalinity of springs is typically less than 5 mg/L and conductivity less than 50 µS/cm. In contrast, wells typically have much higher alkalinity (typically >70 mg/L) and specific conductivity (~200 µS/cm). Piezometers completed within the hill of the Kauffman site indicate a steep downward flow gradient at the horizon of the LK coal. Between the lower permeability of the unweathered-rock zone and the downward component of much of the flow, little water from the unweathered-rock zone is contributed to the springs. It is also apparent that there is a regional distribution of well water alkalinity. Wells on the eastern portion of the area have lower alkalinity than those on the western portion. This pattern is consistent with the higher NP's reflected in the overburden data on the western portion of the site (Fig. 1).

The geologic controls on distribution of calcareous units are complex on this site. Observations of highwalls show that the calcareous material occurs as calcite and minor siderite as cement between sandstone grains in trough bottoms of some channel sandstone (Skema, 1995, personal communication). These calcareous trough deposits are laterally discontinuous and only occur in the basal portion (bottom 3 to 5 m) of a thick (18 to 24 m) channel-sandstone unit. Observations of drill core also suggest that some of the calcareous cement in sandstone is associated with vertical fractures and bedding plane separations. However, calcareous minerals are not found in most fractures.

Overburden holes were paired with wells or springs within 140 m for comparisons of alkalinity of groundwater with overburden NP. NP and alkalinity show a strong positive relationship (Figure 2), with alkalinity (mg/L) being four times the NP value (tons/1000 tons). A similar relationship is seen between specific conductance and NP (correlation coefficient, r = 0.82). As would be expected, specific conductance and alkalinity show a strong positive relationship (r = 0.94). These relationships imply that dissolution of calcareous minerals, where present, has a significant impact on groundwater chemistry.

Sulfate, a conservative aqueous ion, is a weathering product of pyrite. Therefore, a comparison was made between maximum potential acidity (MPA) and sulfate. MPA shows no relation to sulfate in nearby groundwater and has, if anything, an inverse relation to specific conductance. Sulfate concentrations were generally less than 35 mg/L.

Detailed Study of Water Quality at the GR-413 Spring. Zhradnik (1994) investigated the flow patterns in a small area at the Kauffman mine. Five air rotary drill holes (B1 through B-5, Fig. 1) were drilled within the area that apparently feeds groundwater to the GR-413 spring. The drill holes were completed with 2.5-cm-diameter piezometers in the LK coal horizon. The piezometric surface as measured in these five holes is just above the coal elevation, and indicates that water in the coal has a component of flow toward the cropline. Figure 3 is a cross-section showing the stratigraphic and hydrologic relationships up gradient from spring GR 413. The flow of the spring in conjunction with estimated evapotranspiration values indicates that the spring must drain an area of about 140,000 m^2, including the area of holes B-1 through B-5 (Abate, 1993).

Based on four years of quarterly sampling, plus Zahradnik's data, the average specific conductivity of the spring water is 42.9 µS/cm, with a standard deviation of 10.8 (Fig. 4). In contrast, water from the B-series wells ranges from 74 to 270, averaging 171 µS/cm (s.d. 72), or about four times as high. Comparison of Ca, Mg, K, and SO_4 values indicates similar ratios, as indicated in Table 1. During periods of high flow and during many periods of low flow, SO_4 is 7-12 mg/L, but during some periods of low flow, SO_4 increases to 15-25 mg/L, or even higher (Fig. 5). Most of these high SO_4 values are during late winter and early spring. This pattern indicates that most of the year, the spring is fed mainly by dilute water that does not penetrate as deeply as the LK coal horizon. Instead, the spring flow must pass through shallower horizons, very likely in the zone of highly fractured rock described by Hawkins et al. (1996). Hydrographs of this spring (Fig. 6) indicate that rainfall is accompanied almost immediately by a sharp peak in flow resulting from surface runoff (observed at the site), then a few days later by a broader peak that is interpreted to result from flow through the shallow weathered zone. Appreciable storage must exist in this shallow zone to account for the year-round flow of this spring.

MINE B: Wharton Township, Fayette County

The principal coal seam mined at site B is the upper Kittanning (UK). Field pH and specific conductance were measured prior to mining in several uncased drill holes which were completed down to the UK seam. Additionally, numerous UK cropline springs

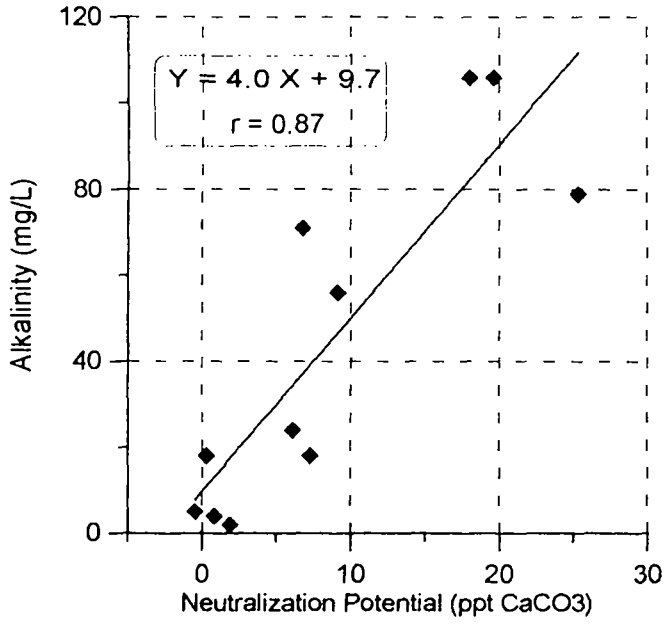


Figure 2. Alkalinity of groundwater associated with the lower Kittanning coal seam as a function of NP at mine site A.

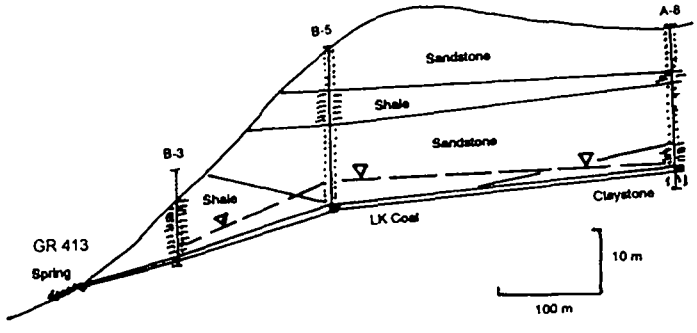


Figure 3. Cross-section through the area of GR-413.

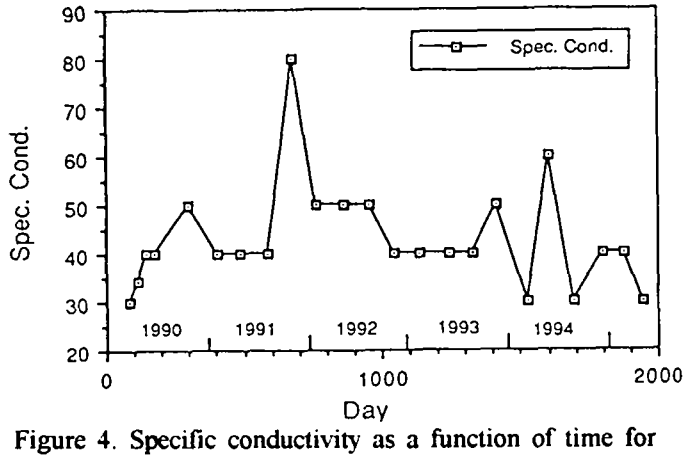


Figure 4. Specific conductivity as a function of time for spring GR-413.

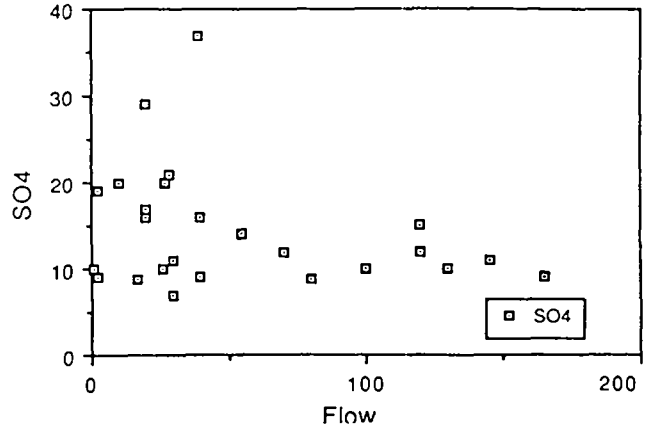


Figure 5. Sulfate as a function of flow. Note higher sulfate values during low flows.

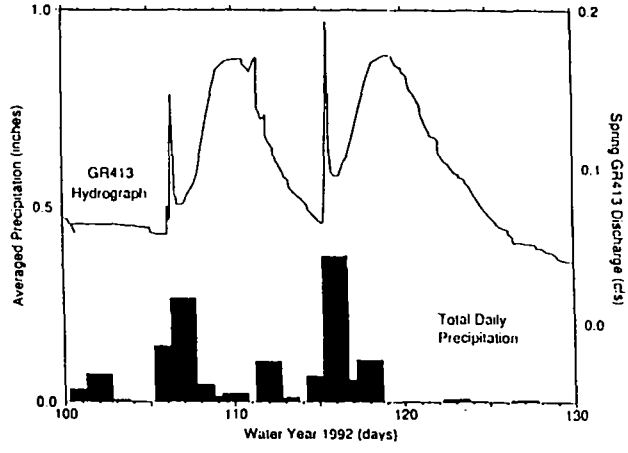


Figure 6. Spring GR-413 response to individual storm events. The initial spikes are from surface runoff (from Abate, 1993).

Table 1. Representative chemical data for the GR-413 spring area (Zahradnik, 1994).

Constituent	B-1	B-2	B-3	B-5	GR-413
SiO_2 (mg/L)	4.7	6.3	4.9	4.2	2.2
Ca (mg/L)	7.9	11.5	4.5	26.7	1.7
Mg (mg/L)	5.2	8.9	3.4	4.8	1.9
Na (mg/L)	4.5	4.5	2.8	1.3	.3
K (mg/L)	3.2	3.1	3.6	3.3	1.2
HCO_3 (mg/L)	6.1	0.0	4.9	14.6	2.4
Cl (mg/L)	3.1	2.3	2.2	2.2	0.7
SO_4 (mg/L)	28.1	97	15.7	14.1	8.9
pH	6.5	3.9	6.5	6.9	5.6
Sp. Cond. (µS/cm)	120	240	80	180	40
Temp. (°C)	11	10	11	9	14

Date of Sampling: Dec. 5, 1993. Oct. 28, 1995 data shows similar relations.

were sampled during collection of background data. Figure 7 is a map showing the Upper Kittanning coal cropline and water sample points.

The specific conductivity of the crop springs and shallow (near crop) wells have lower values (38-62 μS/cm) than the drill holes located toward the middle of the hill where depth to the coal is the greatest (158-221 μS/cm). The pH of the springs is also lower than the wells. NP is negligible in areas with less than 9-12 m of cover, evidently because of weathering (Fig. 8). The higher pH and conductance increase are both coincident with an increase in NP (Fig. 8 and 9). The water in deeper drill holes exhibits higher dissolved solids than in cropline springs and holes with shallow cover, due to the increasing abundance of calcareous minerals with increasing overburden thickness. The spring water is very similar in quality to that of the shallowest drill holes. The high NP strata are freshwater limestones and calcareous shales. The geology of this area is addressed in Brady et al. (1988), where the mine site is refered to as area "C".

Cropline springs have alkalinity between 1 and 9 mg/l. Unfortunately, alkalinity was not sampled in the drill holes, but it is a near certainty that the alkalinities were higher, judging from elevated pH and conductance. This hilltop has been mined and reclaimed and is producing drainage with an average alkalinity of 380 mg/L.

MINE SITE C: Lower Turkeyfoot Township, Somerset County

Mine Site C (Fig. 10) is an example of a site lacking significant calcareous overburden rock within the proposed mine area. This deficiency is shown by the low NP's of the two overburden holes (OB-A and OB-C), and by the low alkalinity of cropline springs, small country bank mines, and water collected from the two overburden holes, which were uncased down to the coal. Near the actual area mined, the highest alkalinity is 11 mg/L from cropline spring SP-14. Two of the springs below the coal cropline have alkalinity as high as 31 mg/L. Apparently calcareous strata exists below the coal.

The two overburden holes encountered predominately sandstone, with coal at 16.4 m and 22.4 m for OB-A and OB-C respectively. The highest neutralization potential in OB-A is 19 tons/1000 tons, the highest in OB-C is 15 tons/1000 tons. The highest percent sulfur (excluding the coal) in OB-A was a 0.3 m binder within the coal bed that had 2.0 percent sulfur (% S). A 1.2 m-thick shale overlying the coal contained 0.5 % S. The highest percent sulfur in OB-C was the shale below the coal, which had 1.7 % S. The next highest sulfur in the overburden is only 0.2 %. The overburden shows the presence of acid-producing strata, but lacks alkalinity producing strata.

Table 3 compares rock chemistry and water chemistry in the two overburden drill holes. The water quality is consistent with the overburden data in indicating a lack of calcareous rocks. Because of the lack of naturally occurring calcareous rocks, an average of 45 tons $CaCO_3$/acre was brought to the site. Additionally, the material with percent sulfur greater than 0.5 % was selectively placed in "pods" that were located such that they would be above the postmining water table. Twenty tons/acre of the alkaline material was placed on the pit floor, with most of the remainder mixed into the high-sulfur spoil pods. Analyses of water from sample point SP-14, within a year after backfilling was completed, show degradation due to mining (Table 3). Evidently the amount of alkaline material added was inadequate to prevent acidic drainage.

Figure 10 includes water quality for some springs, up slope and to the north of the mine site, that have higher alkalinity (35 to 52 mg/L) than cropline springs. The recharge of these springs is stratigraphically and topographically higher than the upper Freeport coal. The Glenshaw Formation, which is the unit from which these springs arise, is known to contain several calcareous marine zones (Flint, 1973). These higher alkalinities may indicate that there is some calcareous material preserved within the shallow groundwater flow system and/or the springs may be receiving some water from a deeper source. Although no deeper well data exists for the Glenshaw Fm. in the immediate area of the mine site, a 40 m deep well 3 km north-northeast of the site, which penetrates the lower portion of the Glenshaw Formation, has alkalinity of 106 mg/L, conductance of 260 μmhos/cm, and sulfate of 9 mg/L (Tom McElroy, 1995, personal communication). Although these data are limited, it appears that wells within the Glenshaw Formation also have higher alkalinity than springs associated with the same strata.

Comparison with Other Parts of the Appalachian Basin

Climate in the Appalachian Basin from Pennsylvania to Alabama is fairly similar. Average annual temperature in the north is ~10° C and in the south >15° C. Precipitation also increases from north to

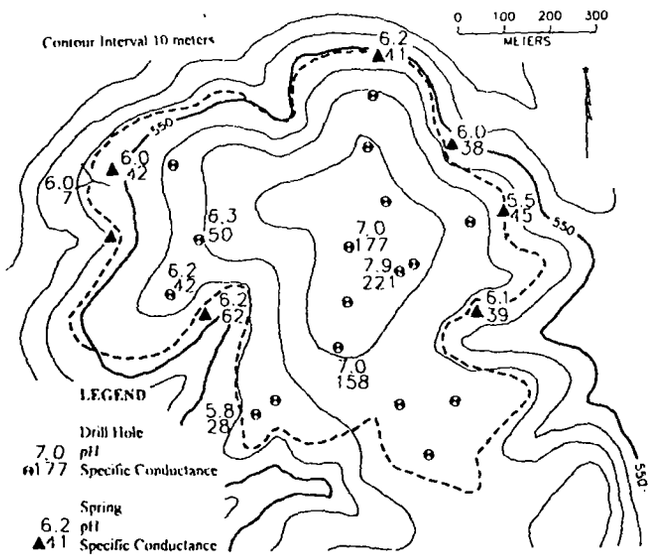


Figure 7. Location of cropline, drill holes and water sample points, and water quality data at mine site B.

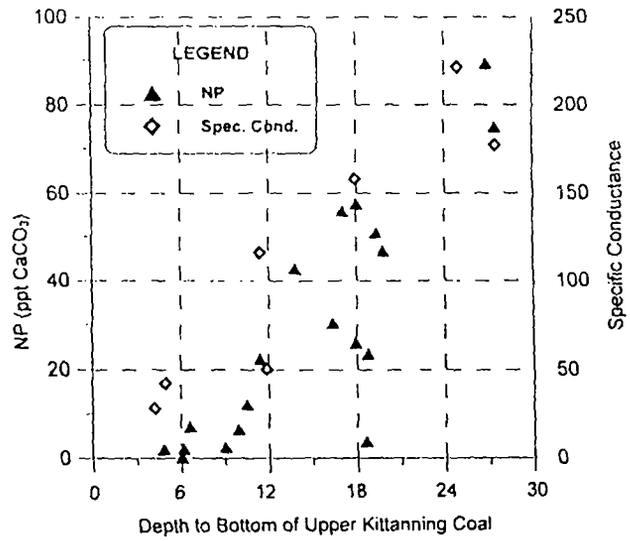


Figure 9. NP and specific conductance (μS/cm) as a function of depth (meters) from the surface to the bottom of the upper Kittanning coal seam for overburden holes (NP), and drill holes and springs (alkalinity).

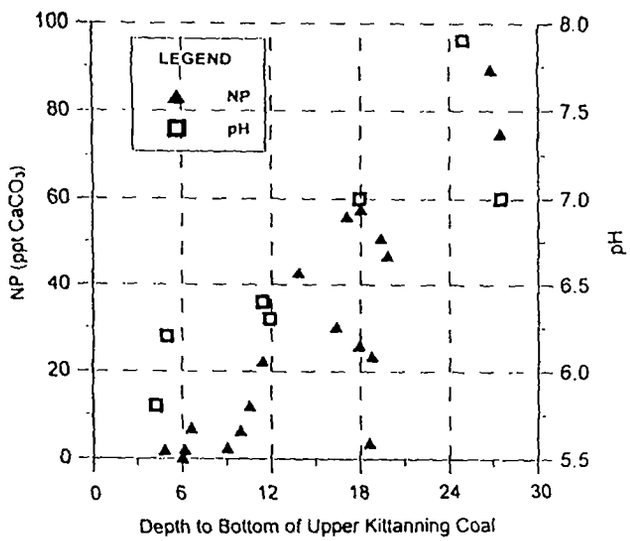


Figure 8. NP and pH as a function of depth (meters) from the surface to the bottom of the upper Kittanning coal seam for overburden holes (NP), and drill holes and springs (alkalinity).

Table 2. Overburden and water quality comparisons for drill holes OBA and OB B on Mine Site C.

Drill Hole	Parameter	NP (ppt)	Alkal. (mg/L)	MPA (ppt)	SO_4 (mg/L)
OB A	ABA (1)	3.5		4.4	
	ABA (2)	0.0		2.4	
	water		5.5		34
OB B	ABA (1)	4.5		2.8	
	ABA (2)	0.0		1.0	
	water		6.5		10

Notes: NP, neutralization potential; MPA, maximum potential acidity. ABA (1) is the traditional method of ABA computation, which includes all determined NP and MPA values. ABA (2) computations were made such that all NP's < 30 and % S's < 0.5 are assigned a value of zero. Methods of computation from Smith and Brady (1990).

Table 3. Postmining water quality at SP-14.

Date	pH	Acidity (mg/L)	Mn (mg/L)	Al (mg/L)	SO_4 (mg/L)
1/12/94	3.7	22	33	35	930
4/21/94	3.8	434	54	54	434

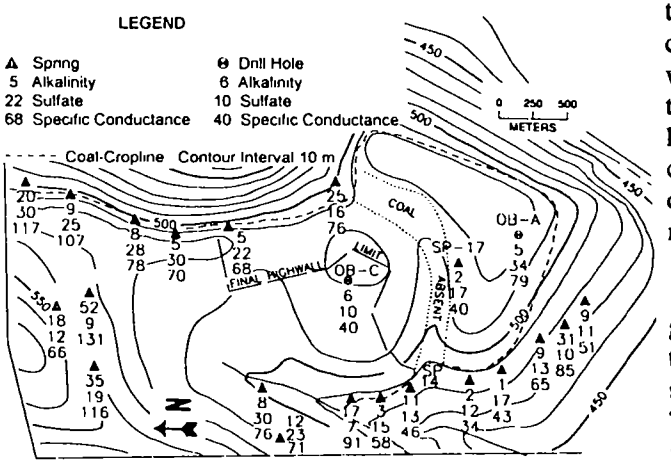


Figure 10. Locations of coal cropline, water sample points, select water quality parameters and overburden holes for mine site C.

south, with rainfall averaging 90 cm in northern Pennsylvania to more than 140 cm in Alabama (Weeks et al., 1968). Annually the infiltration rate of water is sufficient that groundwater is continually flushed through the rock strata from recharge to discharge points. This flow tends to leach out the more soluble minerals. Therefore, shallow groundwater on the Appalachian Plateau has low dissolved solids compared with arid regions.

Geology throughout the Appalachian Plateau is also similar in many respects. The rocks are predominately flat-lying, consisting of sandstone, conglomerate, siltstone, shale, claystone, limestone and coal (Miller et al., 1968). Hills have been subjected to stress-relief forces which have intensified fracturing and subsequently weathering of the slopes, and resulted in higher permeabilities within the weathered zone (Hawkins, et al., 1996). These geologic and climatologic factors result in similar groundwater hydrologic characteristics throughout the plateau.

Numerous studies have investigated the groundwater hydrologic characteristics on the Appalachian Plateau, but very few studies have related the hydrology, groundwater chemistry and rock chemistry. Powell and Larson (1985) investigated water quality in an unmined watershed in a coal-producing region of the Appalachian Plateau of southwestern Virginia. The rock strata are in the Pennsylvanian Norton Formation. The most common carbonate present was siderite, following by calcite and dolomite. Minor amounts of pyrite were generally associated with coal and adjacent strata. They observed that water from springs typically had lower concentrations of alkalinity and dissolved solids than water from dug and drilled wells (Fig. 11). The springs typically have lower alkalinity than dug wells, which have lower alkalinity than drilled wells. Sulfate concentrations are similar for springs, dug wells and drilled wells (with one exception, SO_4 was less than 40 mg/L).

Powell and Larson (1985) envisioned two groundwater flow systems in their study area. One of these "moves under and through the weathered rock or soil layer along the surface of the consolidated rock." The other system "flows through rock fractures and provides the main source of domestic supply" (most domestic supplies were drilled wells). Water in the shallow flow system flows relatively rapidly through rocks thoroughly leached of calcareous minerals. A few of the springs, and many of the deeper waters have high alkalinity (>100 mg/L) (Fig. 11). The high alkalinity springs probably issue from deeper flow systems; however these are the exception rather than the rule.

Singh et al. (1982) in a study of the Mahoning Sandstone in Preston Co. WV, found a weathered zone of about 6 m deep which was low in sulfur and "exchangeable bases" (e.g., Ca and Mg). This indicates that both pyrite and calcareous minerals were removed by weathering within this zone. Brady et al. (1988), in a study that included the area of Mine C of this study also documented the loss of calcareous minerals within ~6 m of the surface. These findings on surface rock-weathering are consistent with the current study.

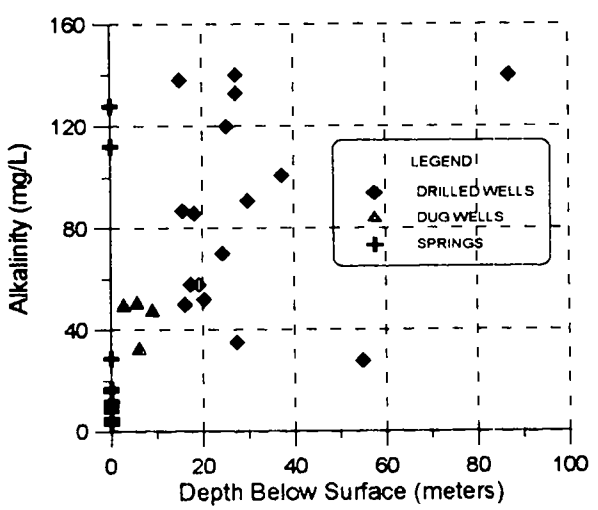


Figure 11. Sulfate as a function of depth of groundwater sample souce in Buchanan Co., VA. Springs are shown at zero depth. Data are from Powell and Larson (1985).

The combined observations of Powell and Larson (1985), Singh et al. (1982), Brady et al. (1988), and this study show evidence for a shallow chemically and physically weathered zone, and two separate shallow flow systems. Figure 5 in the companion paper (Hawkins et al., 1996) is our conceptual model of groundwater flow on the Appalachian Plateau. The literature review in Hawkins et al. (1996) demonstrates the consistency of groundwater hydrologic properties throughout the Appalachian Plateau. Although less research has been done on rock and water chemistry, that which has been done shows results similar to those in PA. It appears that the principals observed in Pennsylvania are applicable to much of the Appalachian Plateau.

Discussion

Surface mining in Pennsylvania mainly occurs within 30 m of the surface and most mines are in groundwater recharge areas (e.g., hilltops). A common misconception has been that water quality of cropline springs in unmined areas is typical of water associated with the coal seam. As illustrated at Mine Sites A and B, water associated with coal- cropline springs can be much more dilute than water from the same coal seam under deeper overburden cover. The cropline springs and shallow wells represent water flowing through the near-surface weathered-rock zone. This weathered-rock zone is quite permeable due to chemical and mechanical weathering. Typically calcareous minerals are absent or negligible within this weathered zone. The rapid flow-through time for the water along with the leached nature of the weathered-rock zone results in water that lacks alkalinity and contains low dissolved solids.

Wells penetrating deeper overburden are completed in unweathered or less weathered materials with lower permeability. Groundwater flow is primarily along fractures and bedding planes. The combination of calcareous minerals, and longer residence time for the groundwater, results in significant dissolution of calcareous minerals forming bicarbonate alkalinity. Downward flow and substantially lower hydraulic conductivities probably result in little of this water reaching the cropline springs.

Mine Site C is an example of a site that lacks significant calcareous rocks. This situation persists from shallow cover to deep cover (maximum overburden that would be disturbed by mining). The lack of calcareous rocks is confirmed by the chemistry of the two overburden test holes and water quality associated with springs, country bank mines, and the overburden drill holes.

From Mine Sites A and B there appears to be a direct relationship between the amount of calcareous material preserved in the overburden and the alkalinity, conductivity and pH of the groundwater. No such relationship exists when comparing MPA (i.e., percent sulfur) with sulfate, probably because of the very limited oxidation of pyrite under saturated conditions. Calcareous minerals are rather soluble in groundwater, whereas pyrite is not. The acid in acid mine drainage is not produced by a simple dissolution process, but by an oxidation process. Pyrite in unmined areas remains largely in an unoxidized state. Premining water quality in deeper drill holes provides a second confirmatory tool, along with acid-base accounting NP, to determine the relative presence or absence of calcareous rock and its distribution within the proposed mine area.

Conclusions and Implications

All of the Pennsylvania sites studied were isolated hilltops within groundwater recharge areas. In all cases the coal cropped out on the sides of the hill. The dominant flow systems for all mines are relatively shallow, with the deepest monitoring wells (completed to the coal seam) on the order of 35 m deep. Where conditions are similar to those given in the examples above, groundwater alkalinity reflects the presence or absence, and abundance, of calcareous rock.

Water quality is directly related to the flow path, the dissolution of material contacted by the groundwater, and the contact time of the water with the rock.

Cropline springs and shallow wells (6 to 9 m deep) that have low or no alkalinity are indicative of shallow leached/weathered overburden. No significant NP's are likely to occur within this zone. Where calcareous rocks are present, such as some deeper cover situations, the calcareous minerals will dissolve in the water and can be measured as alkalinity. Low alkalinity in well or spring water indicates the absence of calcareous strata within the groundwater flow path for that well or spring. It might be expected that sulfate would reflect the amount of pyrite that is present, but there is no relationship between the amount of pyrite (in terms of MPA) and sulfate concentration, thus indicating that pyrite oxidation prior to mining is negligible.

The findings of this study have several important implications:

(1) Coal cropline springs typically reflect very shallow flow through a weathered rock zone and do not necessarily reflect water quality under deep groundwater conditions. Wells are needed to ascertain water quality in the deeper groundwater systems.

(2) Groundwater chemistry, when used with groundwater hydrologic data, can help in better defining groundwater flow systems.

(3) There is a relationship between overburden neutralization potential and groundwater chemistry. If the site is hydrologically isolated such that the only recharge to the site is precipitation, and if alkalinity in wells is high (> 50 mg/L), calcareous minerals are within the flow system and probably near the water sampling point. Where alkalinity is low in wells or springs (< 15 mg/L), the recharge area lacks appreciable calcareous rock.

(5) Groundwater alkalinity can be used to help determine whether overburden sampling for NP has been representative. If overburden analysis does not indicate significant calcareous rocks to be present, but water from wells into the same units are alkaline, the overburden sampling may not be representative of site conditions and additional overburden drilling and testing would be warranted. The combination of groundwater and overburden chemistry can be used together to better define the extent of calcareous overburden.

(6) Overburden sampling and water sampling must represent both shallow and deep overburden cover to adequately represent the entire mine-site hydrology and overburden chemistry. Holes drilled at greater than the maximum cover to be mined may overestimate NP in the overburden that will be disturbed by mining.

(7) There is no relationship between MPA in the overburden and sulfate in the groundwater, or for that matter, between MPA and any other measured parameter. Sulfate in groundwater from unmined watersheds is typically less than 40 mg/L, regardless of flow system.

(8) The above conclusions are probably applicable to a large portion of the Appalachian Plateau. However, the applicability to areas with different climate, physiography and/or geology is unknown.

Acknowledgments

We thank Tom McElroy, Evan Shuster, Gary Fleeger and an anonymous reviewer for their comments.

References

Abate, C., 1993. A Numerical Modeling Approach to Estimation of Parameters Describing Groundwater Flow in Coal-Bearing Rocks of the Allegheny Plateau. Ph.D. thesis, Pennsylvania State Univ., 144 p.

Berg, T..M., J.H. Barnes, W.D. Sevon, V.W. Skema, J.P. Wilshusen, and D.S. Yannacci, 1989. Physiographic Provinces of Pennsylvania. Map 13, PA Bureau of Topographic and Geologic Survey.

Brady, K.B.C., J.R. Shaulis, V.W. Skema, 1988. A study of mine drainage quality and prediction using overburden analysis and paleoenvironmental reconstructions, Fayette County, Pennsylvania. Mine Drainage and Surface Mine Reclamation, v. 1, no. 1: Mine Water and Mine Waste, U.S. Bur. of Mines Info. Circ. 9183, p. 33-43.

Cravotta, C.A. III, K.B.C. Brady, M.W. Smith, and R.L. Beam, 1990. Effectiveness of the addition of alkaline materials at surface mines in preventing or abating acid mine drainage: Part 1. Theoretical considerations. In: Proceedings of the 1990 Mining and Reclamation Conference and Exhibition. Charleston, WV, April 23-26, 1990. p. 221-225.

Evans, D.R., 1994. Geochemical field evaluation of a lime addition method for inhibiting acid mine drainage from coal mine spoil, Clearfield County, Pennsylvania. M.S. thesis, Pennsylvania State Univ., 171 p.

Flint, N.K., 1965. Geology and Mineral Resources of Southern Somerset County, Pennsylvania. County Report 56A, PA Geologic Survey, 267 p.

Hawkins, J.W., K.B.C. Brady, S. Barnes, and A.W. Rose, 1996. Shallow ground water flow in the northern Appalachian Plateau: Part 1. physical characteristics. In these proceedings.

Kipp, J.A. and J.S. Dinger, 1987. Stress-relief fracture control of ground-water movement in the Appalachian Plateaus. Presented at: National Water Well Assoc., Focus Conference on Eastern Regional Ground-Water Issues, July 15, 1987, Burlington, VT, 16 p.

Miller, R.L., J.B. Hadley, and D.P. Cox. 1968. General geology. In: Mineral Resources of the Appalachian Region, U.S. Geological Survey Prof. Paper 580. p. 64-68.

Powell, J.D. and J.D. Larson, 1985. Relation between ground-water quality and mineralogy in the coal-producing Norton Formation of Buchanan County, Virginia. U.S. Geological Survey Water-Supply Paper 2274, 30 p.

Rose, A.W., L.B. Phelps, R.R. Parizek and D.R. Evans, 1995. Effectiveness of lime kiln flue dust in preventing acid mine drainage at the Kauffman surface coal mine, Clearfield County, Pennsylvania. In: Decades Later: A Time for Reassessment. Am. Soc. for Surf. Mining and Reclamation 12th Annual Mtg., v. 1, p. 159-171.

Singh, R.N., W.E. Grube, Jr., R.M. Smith, and R.F. Keefer, 1982, Relation of pyritic sandstone weathering to soil and minesoil properties. In: Acid Sulfate Weathering, Soil Science Society of America, p. 193-208.

Smith, M.W. and K.B.C. Brady, 1990. Evaluation of acid base accounting data using computer spreadsheets. In Proceedings: Mining and Reclamation Conference and Exhibition, Charleston, WV, April 23-26, 1990, p. 213-219.

Weeks, R.A., R.D. Zahnizer and L.L. Chute, 1968. Geography. In: Mineral Resources of the Appalachian Region. U.S. Geological Survey Professional Paper 580, p. 27-30.

Zahradnik, J., 1994. A comparison of ground water vs. spring water geochemistry to evaluate acid forming potential of overburden at the Kaufmann Surface Mine, Clearfield County, Pennsylvania. Unpublished senior thesis, Pennsylvania State University, 37 p.

MINE SEEPAGE PROBLEMS IN DRIFT MINE OPERATIONS

By

Clyde DeRossett, David E. Johnson, and David B. Bradshaw

Abstract. Extensive mining in the Eastern Kentucky Coal Region has occurred in coal deposits located above valley floors. Underground mines present unique stability problems resulting from the creation of mine pools in abandoned works. "Blowouts" occur when hydrostatic pressures result in the cataclysmic failure of an outcrop- barrier. Additionally, seepage from flooded works results in saturation of colluvium, which may ultimately mobilize as landslides. Several case studies of both landslides and blowouts illustrate that considerations should be taken into account to control or prevent these problems.

Underground mine maps and seepage conditions at the individual sites were examined to determine the mine layouts, outcrop-barrier widths, and structure of the mine floors. Discharge monitoring points were established in and near the landslides. These studies depict how mine layout, operation, and geology influence drainage conditions.

The authors suggest that mine designs should incorporate drainage control to insure long-term stability and limit liability. The goal of the post-mining drainage plan is control of the mine drainage, which will reduce the size of mine pools and lower the hydrostatic pressure. Recommendations are made as to several methods that may be useful in controlling mine drainage.

Additional Key Words: mine seepage, landslides, mine blowouts

Introduction

Extensive mining in the Eastern Kentucky Coal Region has occurred in coal deposits located above valley floors. These drift mines present unique stability problems resulting from the creation of mine pools. These pools can cause cataclysmic failure of outcrop-barriers, referred to as "blowouts". Another condition caused by mine pools is sudden increases in seepage from the mine works causing saturation of the colluvium, resulting in landslides. A recent blowout and two landslides were selected for case studies. These studies illustrate seepage problems encountered by drift mine operations, demonstrating the need for planned mine drainage. Recommendations are made as to several methods that may be useful in controlling mine drainage.

The groundwater flow of an undisturbed mountain in Eastern Kentucky is primarily through fractures and colluvium on the exterior portion of the mountain. This flow will recharge perched aquifers during wet seasons. The water stored in the aquifers will provide base flow to the

[1]Paper presented at the 1996 National Meeting of the American Society for Surface Mining and Reclamation, May 18-23, 1996.

[2]Clyde DeRossett, Environmental Engineer, David E. Johnson. Registered Geologist, David B. Bradshaw, Registered Geologist, Kentucky Department for Surface Mining Reclamation and Enforcement. Frankfort, Kentucky.

mountain's exterior during the dry season. Wide distribution of stress-relief joints on the mountain, and the existence of perched aquifers help to keep the groundwater flow diffused. For additional study of groundwater flow in the area see Kipp and Dinger (1987) and Harlow and LeCain (1991).

The creation of a mine void will tend to concentrate groundwater, causing a change in groundwater flow patterns . This process is enhanced through fracturing caused by high-extraction techniques. Fractures created by mining provide better conduits into the mine void, draining overlying perched aquifers. Even installation of roof bolts may provide increased flow into the mine, if the drill holes penetrate a low hydraulic conductivity stratum in order to anchor into an overlying unit with a higher hydraulic conductivity. At the elevation of the mine works, groundwater flow changes from fracture-dominated to dip-controlled flow. Drainage into the mine will then be directed towards the mine pools, allowing a build-up of hydrostatic head and creating potential seepage areas when these pools intersect the joint system.

Concentration of Groundwater Flow

Case Study 1

Examination of a mine in Floyd County, Kentucky, is a good example of how a mine void concentrates diffuse groundwater flow. This study was based on an investigation of a slide that occurred in a small hillside drain in Southeastern Floyd County. At this site, two items were studied: a comparison of the volume of discharge from the slide area with the volume of measured rainfall, and a comparison of the discharge from the slide with flow from an undisturbed watershed (Figure 1).

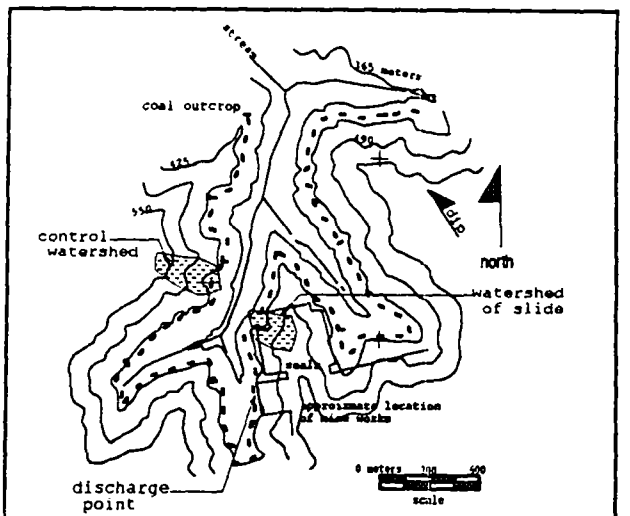


Figure 1. Area of watersheds at case study no. 1

Both the watershed of the slide and the control watershed have similar size and topography, and both were forested with little surface disturbance. The slide's watershed is 4.5 ha. (11 acres) and the control watershed is 5.5 ha. (13.5 acres). No known mining has occurred under the control watershed, but underground mining has occurred in the Amburgy coal seam to the ridge line behind the watershed. The underground works are approximately 305 meters west of the outcrop, and the nearest pillaring is 490 meters to the east. Underground mining in the Amburgy coal seam has occurred under the watershed of the slide. Mine works exist to within 60 meters of the crop line and the nearest pillaring is 80 meters from the crop line.

Monitoring points were established and flow rates were monitored from August, 1994, to May, 1995. In the mine-affected watershed, three monitoring points were established near the base of the slide in order to measure the total discharge leaving the slide area. One monitoring point, that should have intercepted most of the drainage, was established in the control watershed.

During this study, the control watershed seldom flowed, with the only measured flow occurring on May 15,

1995. After establishing the monitoring point, a small point-discharge from the colluvium was discovered below the monitoring point. This point flowed for a few days at an estimated peak flow of 11 liters-per-minute during wet periods of the year, when the colluvium was saturated. Discharge from the point was observed only three times after heavy rainfall events in January, March, and May.

The affected watershed flowed constantly throughout the study, with flow rates ranging from 17.4 to 435.3 liters-per-minute. After one storm in January, 1995, the measured peak flow was 155.0 liters-per-minute, while the control watershed had a flow of less that 11.0 liters-per-minute. Four days after the storm, the flow rate in the affected watershed was 30.3 liters-per-minute, while the control watershed had stopped flowing.

The second item studied was a comparison of the volume of rainfall with the flow measured in the mine-affected watershed. Flow rates and on-site rain-gauge measurements were recorded from September, 1994, to January, 1995. A Belfort rain gauge (Model 5-780) recorded the amount and time of precipitation at the site. Flow was measured intermittently. Results of the volumetric calculations indicated that approximately 63 percent of the measured rainfall volume that fell in the watershed was measured at the monitoring points. This percentage of precipitation as flow is considered low, because the discrete monitoring probably did not always measure the peak flows. The monitoring points only measured a portion of the water coming from the mine void, with an unknown amount being discharged as subsurface flows.

The amount of groundwater coming from the slide area is considered high when compared to studies done by others. Analysis of stream flow hydrographs done in the watershed of Russell Fork near the Kentucky-Virginia border, estimated approximately 18 percent of precipitation was available for groundwater discharge. It was estimated that approximately 50 percent of the rainfall was lost to evapotranspriation (Larson and Powell 1986). This is in rough agreement to earlier estimates done at other large drainage basins in Eastern Kentucky showing approximately 67 percent of the rainfall lost to evapotranspriation (Price 1962). While direct comparison with these large watersheds may not be applicable, they do support the view that seepage seen in the study watershed was more than would be expected from the watershed.

Results from short-term monitoring of the two watersheds clearly showed that mining had affected groundwater flow in the slide area. The mine-affected watershed showed a constant flow that could vary greatly and produce large flow rates not noticed by the landowners before the mining operations. The mine pool feeding the seepage area had good storage, as evidenced by the constant flow rate and a total discharge volume of 222,202 cubic meters (18 acre-feet), from August 1994 to May 1995. High specific conductance measurements, often associated with mine drainage would also support the view that much of the water is coming from the mine. Comparison of the specific conductance taken in the control watershed would support this conclusion (Figure 2).

Mine Blowouts

The most drastic result of improper drainage control is the occurrence of mine blowouts from drift mines. These events can result in the sudden release of force that can endanger the public and cause substantial environmental damage in a few hours. From the spring of 1993 to the spring of 1994, five mine blowouts were studied. All the sites had one

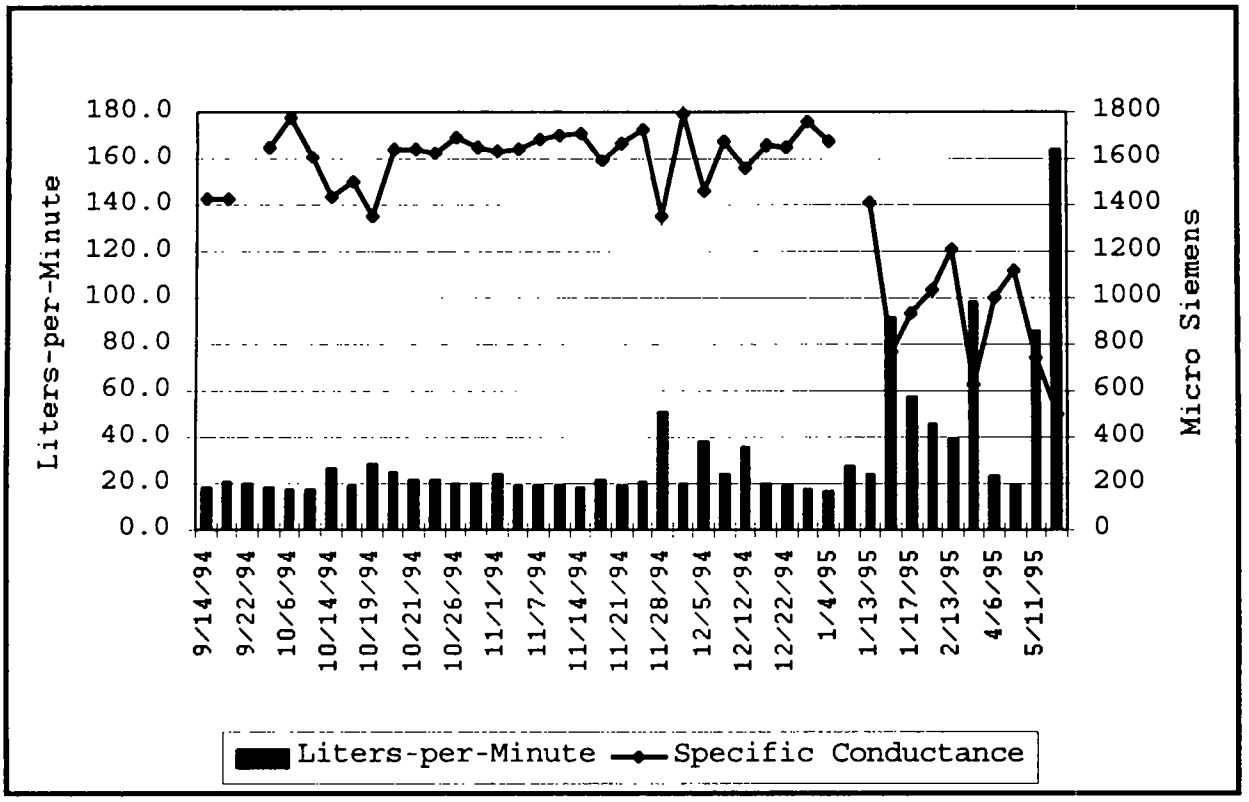


Figure 2. Discharge and Specific Conductance measurements for monitoring point No. 3, Case Study 1.

item in common: the events occurred at excessively weakened outcrop-barriers. These were either at extremely narrow outcrop-barriers or at intersections with small unknown mine works.

Case Study 2

At one study site, the blowout occurred where the outcrop-barrier was approximately 5 meters wide. The resulting blowout formed a gully in less than 3 hours and moved at least 3,600 cubic meters of colluvium. The effects of the sudden discharge blocked a stream, damaged several small bridges downstream, and blocked the road into a community over one mile away. The mine works associated with the blowout covered approximately 113 ha (280 acres) and had been active for approximately 3 years. The mining was completed in 1986, eight years before the blowout.

In addition to the blow out, there were two other small surface discharges located in the area. These were small discharges, one site had only diffused seepage in the area of the portals (no measurements taken). The second seep had a flow rate measured from 19 to 38 liters-per-minute, based on infrequent sampling done over the period from March, 1994, to March, 1996. The layout of the mine was such that almost all of the mine drained to the area of the blowout. The difference in elevation between the high and low points in the mine was almost 15 meters. The low point was located in the area of the seep (Figure 3) with the blowout occurring approximately 9 meters below the highest point of the mine. The two surface discharges were located close to each other and along with the configuration of the mine floor helped to reduce the water level in the mine pool during periods of low inflow, reducing the hydrostatic pressure in the area of blowout.

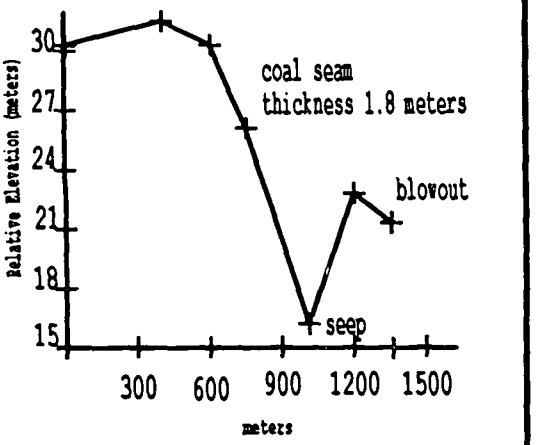


Figure no. 3. Profile of mine floor along drainage path in mine.

Measurements taken after the blowout showed a trend of reduced flow. While no attempt was made to account for the various factors influencing the flow from the blowout area, the measurements do indicate that a considable amount of water was stored in mine voids (Figure 4). Measurements over the period from February, 1994, to September, 1995, showed a downward trend indicating a reduction of storage in the mine. The main lessons to be learned from the study of this site were that control of the mine's outcrop-barrier and the size of the collection basin is necessary in order to lessen the chance and severity of the mine blowout.

Study of the dataset would also indicate that none of the mine blowouts occurred in areas where modest amounts of outcrop-barrier were maintained to resist the pressure. None of the cases examined indicated the Ashley or Mine Inspector Formula was invalid. This would support the use of the formula for the design of outcrop-barrier widths. However, the Ashley Formula only indicates the needed coal-pillar width (Chekan 1985). The coal seam may not be the structurally weakest member containing the mine pool, due to the topography of the hillside.

Mine Seepage Problems

The second stability problem associated with mine drainage is the saturation of outslopes resulting from seepage through outcrop-barriers. This problem is much harder to control than mine blowouts. Seepage from mine pools will result in saturation of colluvium on the outslope, sometimes resulting in landslides. Flow from mine pools to seepage areas is controlled by hydraulic conductivity along the outslopes. The greatest hydraulic conductivity is associated with the stress-relief joint-system. Studies have shown that hydraulic conductivity decreases greatly toward the center of mountains. Studies done in Virginia (Harlow and LeCain, 1991) have shown a large reduction of hydraulic conductivity within 31 meters for most rock strata, except coal, from the outcrop. Stress-relief joints are more open near the surface and close rapidly with increased overburden.

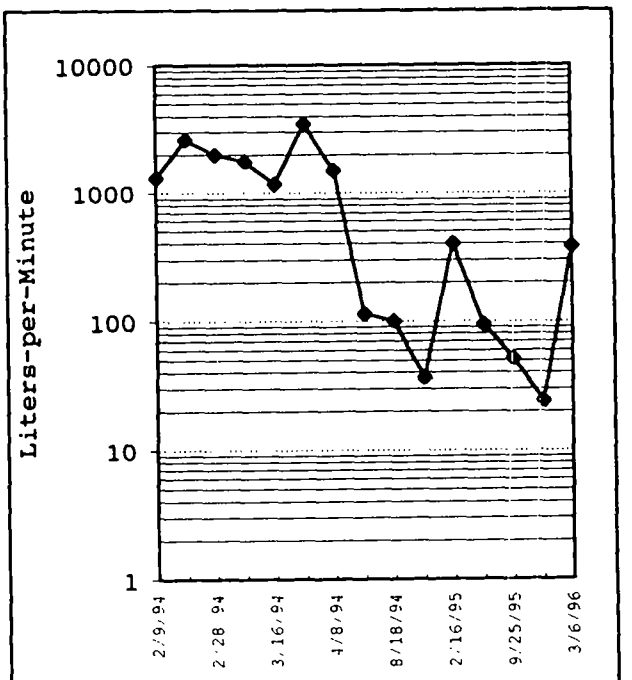


Figure 4. Flow Measurements From Blowout in Case Study No. 2.

A narrow outcrop-barrier will result in a better connection between the joint system and the mine pool. A chart showing a cumulative percentage curve of the width of the outcrop-barrier at the areas of the slides studied is shown in Figure 5. In these studies, the distance from the slide to the mine works has a mean of 45 meters, with a standard deviation of 8.5 meters. The study indicates that outcrop-barrier width is very important in the prevention of slides. However, maintenance of an outcrop-barrier alone will not always guarantee prevention of seepage problems. In case study number one, examination of the mine map indicates that a barrier of 60 meters was maintianed around the whole panel and mine pool. As suggested by Harlow and LeCain, 1991, hydraulic conductivity of the coal seam would decrease with increased barrier width due to the increased overburden depth. The decrease in hydraulic conductivity may allow a build up of the hydrostatic head, thereby increasing the flow through fractures that intersect the mine pool. Though increasing the outcrop-barrier will increase the head loss to the surface-seepage areas, resulting in a reduced flow, their use will not always assure prevention of seepage problems. If that area of the mine has enough inflow, the increase in depth may still provide enough hydrostatic head to cause seepage problems. While the use of increasing outcrop-barrier widths at sensitive areas may prove to be an effective tool, the main objective should be to control the size of the mine pools.

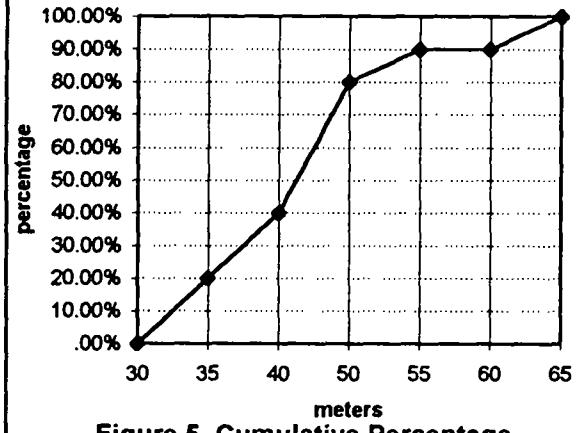


Figure 5. Cumulative Percentage Curve of Barrier Width at Landslides. Data set = 10.

From the case studies, it is clear that control of mine seepage must address both the maintenance of adequate outcrop-barriers width and control of the sizes of the mine pools. The control of the size of the mine pool can be either by planned drainage of the mine or by limiting the size of the drainage area, preventing most of the drainage from collecting into one large pool. Restricting the size of the mine drainage area should be a neccessary part of mine planning. The neglect of this has lead to serious seepage problems.

One method that can be used to control drainage is by planning the layout of barrier pillars in ways that divert drainage to various sections of the mine or to discharge points. While these pillars may allow considerable seepage, their use to divert flow to other areas is considered useful. Mine seals may also play an important part of the mine drainage plan. However, consideration needs to be given to ensure the long-term stability of these structures. Placement of the barrier pillars and mine seals along with the local dip of the coal seam could greatly aid in the control of mine drainage. A good example of this is demonstrated in Case Study 3, where seepage was observed on both sides of the of a small hollow.

Case Study 3

In Case Study 3 the mine map indicates two mine pools. One pool shows a possible collection basin of 40 ha (100 acres) and the other pool is

basically limted to one panel, approximately 8 ha (20 acres), under the ridge. This panel is isolated by the barrier pillars and seals separating the sub-main from this panel. Sampling at several monitoring points was done to investigate seepage conditions. On the side of the large drainage area, the mine pool resulted in a slide and later a blowout. The seepage on the other side of the hollow, while not planned, has not resulted in a slope stability problem. Study of mine maps and monitoring points give some indications as to the differences in the problems seen at the two sides of the mountain.

Sampling was initially started at three sample points; however, one point was removed during stabilization of the slope. Two monitoring points remained allowing continued monitoring of the two mine pools. The most significant finding from the sampling was in the difference in the seasonal fluctuations of the two monitoring points and the reflection of the change of the flow rate at monitoring point 2 (Figure 6), which resulted from reduced hydraulic head caused by a blowout. Monitoring point 2, at the larger mine pool, showed less fluctuation of flow rate, except for one surge in flow due to precipitation. This surge in the flow showed large drops in specific conductance (Figure 7). This observation gives a good indication of how near surface groundwater (with lower specific conductance) affects the two seepage areas. Monitoring point 3 at the small drainage area shows a large downward trend in the flowrate during the dry time of the year. Results of the trends in the amount of seasonal fluctuation of the monitoring points indicated that the volumes of the mine pools are different as suggested by the mine map. The mine pool feeding monitoring point 2 showed less change in the hydraulic head as indicated by a more consistent flow rate, measured at the discharge point. Monitoring at sampling point 3 indicates a larger change in the hydrostatic head. The mine pool at monitoring point 3 is fluctuating more, presumably as a result of less storage capacity and/or lower inflow rates. In April, 1994, a blowout occurred in the area of monitoring point 2 reducing the flow measurements (Figure 6).

The Correlation Coefficient (r)

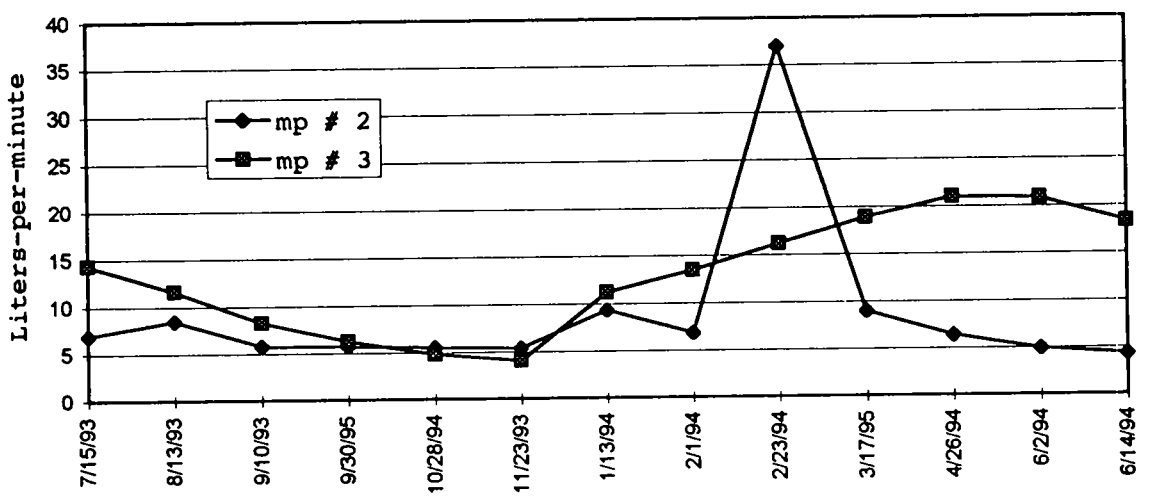


Figure 6. Comparison of Monitoring Points 2 and 3 in Case Study No. 3

was also calculated for the flow rates (the sample set on February 23, 1994, was not used because of the influence of the storm event). The r value for the data set before the blowout had a value of 0.75. The r value for all the data set had a value of 0.09. This change in the correlation of the two monitoring points would indicate that the blowout had affected a change in the hydrostatic head of the mine pool at monitoring point No.2. While the data set is limited and details of the actual drainage conditions and mine pool size are not available, this case study still demonstrates how control of mine drainage areas are important and that planning of the mine layout can reduce the size of the mine pools.

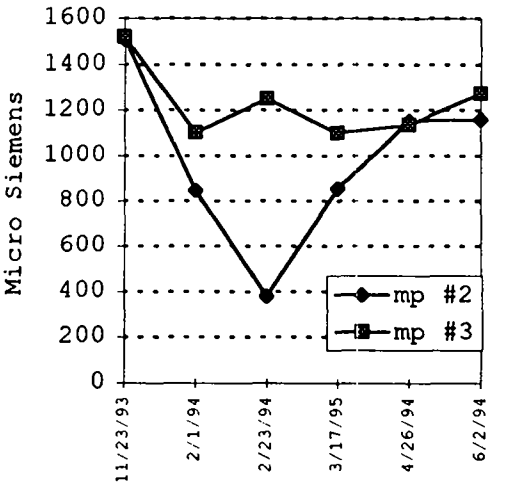


Figure 7. Specific Conductance Values for Case Study No. 3.

Conclusions and Recommendations

These case studies are not detailed investigations of mine drainage control; however the studies show the need to control mine drainage. The study indicates the need to have flexible systems that can take advanage of structural geology, outcrop-barrier width, and drainage points. Planning for drainage control must be flexiable enough to take advantage of the unique conditions that are present in each mine. In planning mine drainage the main concern is in limiting the hydrostatic pressure of the mine pool. Several tools are avialable for control of drainage both into and out of the mine pool. Specifically, the study has found:

*The mining operations will concentrate groundwater flow to specific areas of the mine. Failure to plan for the change in the groundwater flow can result in dangerous and costly environmental problems.

*Outcrop-barrier widths are important in the control of mine seepage. The outcrop-barrier widths seem useful in reducing the hydraulic gradient, causing less flow to specific areas at the outcrop. In areas where the mine pools develop close to the stress-relief fracture system seepage problems will increase. However, the use of a minimum barrier width will not assure prevention of landslides.

*Discharge points provide a method of reducing the volume and hydrostatic pressure at the mine pools. Possible discharge points should be considered where feasible to reduce the amount of water stored in the mine area. These discharge points can provide improvements to the landuse area when the water quality is adequate.

*Study of the mine maps and the flow measurements can give some indications of the mine pool conditions. While this data may be limited in detail on exact drainage areas and area and depth of the impoundment, useful information of the changing conditions of the mine pools can still be obtained. This information may be useful in planning of abandoned mine projects and assessment of potential hazards to the public, or when investigating the potential undermining of mine void.

*The use of barrier pillars and seals needs to be investigated as structures

to reduce the size of the collection basin draining into the mine pool.

References

Chekan Gregory J. 1985, "Design of bulkheads for controlling water in underground mines", U.S. Bureau of Mines Information circular IC9020.

James A. Kipp and James S. Dinger, 1987, "Stress-Relief Fracture Control Of Ground-water Movement In The Appalachian Plateaus". Proceedings Forth Annual Eastern Regional Ground Water Conference, Focus On Eastern Regional Ground Water Issues, July 14-16.

Harlow George E. And Gary D LeCain , 1991, Hydraulic characteristics of, and ground-water flow in coal-bearing rocks of Southwestern Virginia. U.S. Geological Survey Open File Report 91-250.

W. E. Price Jr. , D.S. Mull and Chabot Kilburn ,1962,"Reconnaissance of ground-water resources in the Eastern Coal Field Region, Kentucky". U.S. Geological Survey Water-Supply paper 1607.

Larson J.D. and Powell John D., 1986, "Hydrology and effects of mining in the Upper Russell Fork Basin, Buchanan and Dickenson Counties, Virginia" U.S. Geological Survey Water-Resources Investigations Report 85-42238.

EFFECTS OF SPOIL GROUNDWATER ON WATER-QUALITY IN A RECEIVING LAKE

by

Douglas C. Turney[2], Kenneth B. Edwards[3], and Walter E. Grube Jr.[4]

Abstract. A groundwater and surface-water study was conducted in order to determine the source(s) which are adversely affecting a 35-acre lake in southeastern Ohio. The lake has a pH of 3 and is flanked on the north by about 100 acres of recently reclaimed spoil, and on the south and west by an area of similar size that has not been reclaimed since surface mining ceased over thirty years ago. Inflows into the lake from the north include three major seeps and the outlet of a limestone drain installed early in the recent reclamation. These inflows contribute only about 5 to 10 percent of the total inflow into the lake but have very poor water-quality, with acidities approaching 1800 mg/L as $CaCO_3$. The other major inflows originate to the south and west of the lake and include three streams and Spring U, which account for nearly 70 percent of the total inflow to the lake, but which have lower acidities ranging from -15 to 250 mg/L depending on the time of year. The remaining inflows include groundwater that seeps into the lake. Although the lake receives inflows from other sources, we believe that the groundwater contribution is a significant factor in overall lake-water quality. Coal-seam-elevation data, monitoring-well surveys and estimations from old topographic maps indicate that the dominant groundwater flow is from old underground mines and auger mining north of the site.

Additional Key Words: Spoil, Highwall, Coal Mine, Acid Mine Drainage

---

[1]Paper presented at the 1996 Annual Meeting of the American Society for Surface Mining and Reclamation (ASSMR) in Knoxville, TN, May 19-25, 1996.

[2]Douglas C Turney, Research Assistant, Department of Civil Engineering, Center for Geotechnical and Environmental Research, Ohio University, Athens, OH 45701.

[3]Kenneth B. Edwards, Assistant Professor, Department of Civil Engineering, Center for Geotechnical and Environmental Research, Ohio University, Athens, OH 45701.

[4]Walter E. Grube, Jr., Visiting Professor, Department of Civil Engineering, Center for Geotechnical and Environmental Research, Ohio University, Athens, OH 45701.

Introduction

Acid mine drainage may result from a variety of mining methods performed in a watershed - underground mining, strip mining, and auger mining. The mining process exposes iron sulfide (pyrite) in the sandstone overburden and exposes faces of unremoved coal to air and water. The oxidizing conditions result in a lowering of the pH, increase in acidity, and increase in dissolved metals, leading to an overall degradation of water-quality and the inability to support aquatic life.

The degradation of Howard Williams Lake is the result of surface and underground mining of coal. The pH of the lake varies from 2.9 to 3.5 depending on the time of year and has no signs of any aquatic life. The objectives of our work include determination of the sources of acid water and engineering approaches to improve lake-water quality.

Background and Objectives

Howard Williams Lake is a 0.14 square kilometer (35 acre) reservoir located in Perry County, in southeastern Ohio. It was built before 1950 to provide water for a coal-washing plant farther down the valley. The lake, created by damming the valley, collects water from a 1554 square kilometer (6 square miles) watershed. The lake has had a low pH, around 3.0, for at least two decades, with acidity ranging from 200 to 300 mg/L as $CaCO_3$.

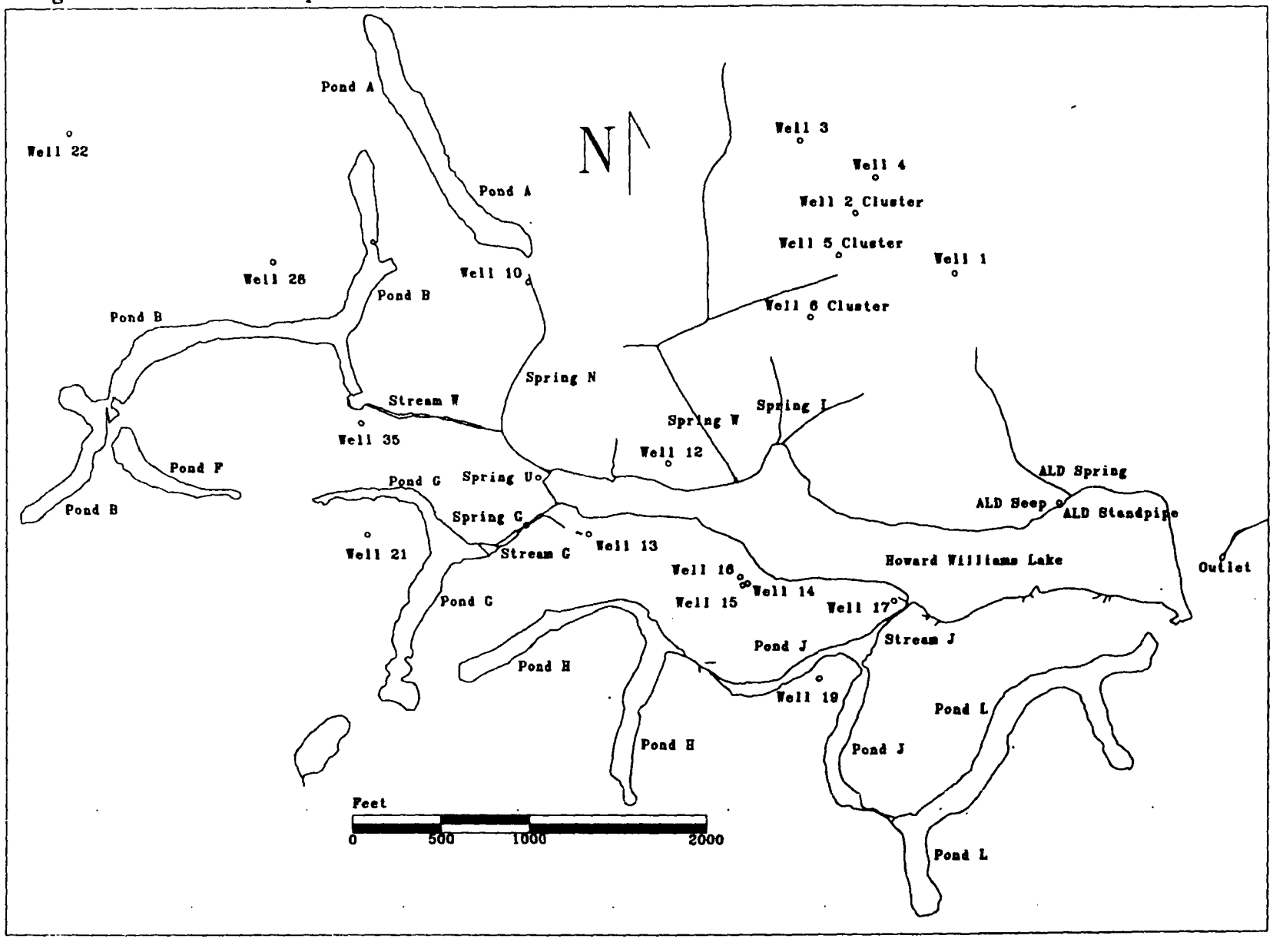
The economic coal seam in this region is the Middle Kittanning (No. 6), which averages about 1.4 meters thick (4.5 feet), with local variations. The outcrop was stripmined by dragline, and auger methods were used at some locations north and south of the lake. The auger system used the "push-button-miner", or PBM, which created rectangular borings about 12-ft in width, rather than the round boreholes common with other augering machines. Coal was also recovered by underground room-and-pillar methods until the late 1960's.

No reclamation of the surface disturbances was done until 1990. At that time the State of Ohio reclaimed about 100 acres north of the lake, primarily in areas where old township roads terminated at the tops of highwalls of about 30.5 meters (100 feet) in height. The spoil was regraded to a rolling topography from the old highwalls to the lake. Compost additions, papermill sludge additions, and revegetation seeding resulted in a current good ground cover of grasses in this reclaimed area.

Acidic waters enter this lake from (1) seeps and surface drainage from the reclaimed area north of the lake, (2) seeps from unreclaimed spoil piles and surface drainage from water ponded in old strip pits south of the lake, and (3) surface drainage from old ponded pits west of the lake. The overburden of the No. 6 seam, and the coal seam itself, contain from a few tenths percent up to several percent sulfur, as pyrite, with very little alkaline material.

The basic mechanism that produces acid mine drainage is the oxidation of pyrite. Pyrite dissolves to form ferrous iron, acidity, and sulfate in equation (1). (Donovan *et al*., 1994; Lapakko, 1994) Both reactions take place in the presence of oxygen and water and are catalyzed by the bacteria *Thiobacillus ferrooxidans*. (White *et al*., 1994)

Figure 1. Site Map.



$$FeS_2 + 7/2O_2 + H_2O \Rightarrow 2SO_4^{2-} + Fe^{2+} + 2H^+ \quad (1)$$

Ferrous iron is then oxidized to ferric iron in the presence of oxygen and it consumes acidity.

$$Fe^{2+} + 1/4\ O_2 + H^+ \Rightarrow Fe^{3+} + 1/2\ H_2O \quad (2)$$

Equation (3) shows that ferric iron in solution will form iron hydroxides and produce acidity, but this is a very slow reaction in waters with a pH below 3. At higher pH values this reaction is very fast, resulting in noticeable quantities of iron hydroxides precipitating out of solution.

$$Fe^{+3} + 3H_2O \Rightarrow Fe(OH)_3 + 3H^+ \quad (3)$$

Methods

Mine maps were obtained from the U. S. Bureau of Mines showing the extent of underground mining in the regions surrounding the lake. A digitized map, derived from aerial photos taken in 1994, of the area around the lake was obtained from the Ohio Department of Natural Resources. Other aerial photos taken at various stages of the surface mining operation were also examined. These, and other anecdotal information, described the deposition of a large volume of coal-washing wastes in a pit along a highwall north of the lake. This waste deposit was covered during the 1990 reclamation; estimates of the volume of this material are about 245,000 cubic meters (320,000 cubic yards).

Study of old maps, photographs, and intensive walk-through of the mined land, highwall exposures, and spoil piles provided definition of the surface waters flowing into the lake. It was expected that surface mining intercepted old deep-mine tunnels, but the bases of all current highwalls are covered with slumped material and water in abandoned strip pits. This prevented clear determination of possible hydraulic connections between underground mined areas and surface water in strip ponds.

Mine maps provided data on the extent of mine voids underneath the rolling hills of the region, underclay elevations, coal-seam thickness, and localized geologic sections. Figure 1 shows the major features of the area around the lake, with individual strip-pit ponds identified.

In early 1994, twenty-four groundwater monitoring wells were installed with the assistance of the Ohio Department of Natural Resources' equipment and staff. Figure 1 shows the locations of these wells. Well clusters were installed at No.2, No.5, and No. 14 to provide opportunities to perform medium-scale hydraulic tests of the minespoil. All wells are either 2-in or 4-in diameter and are screened either 1.5 or 3.0 meters (5 or 10-ft) above the underclay. Well Nos. 4, 19, 21, and 28, were located in attempts to intercept underground mine rooms or auger-mine voids. This was in order to determine water-quality, flow direction, and the extent to which these subsurface voids are flooded. An underground mine room was found at well 21 and an auger opening was found at well 4. Both well Nos. 22 and 28 were drilled into unmined coal.

Well Nos. 1, 2, 3, 5, 6, 10, and 12, are located in recently reclaimed spoil north of the lake. Well Nos. 13, 14, 15, 17, and 35, are located in unreclaimed spoil south of the lake. Wells 1, 2, and 3, are located in the coal-cleaning waste buried in a pit north of the lake.

Surface-water inflows to the lake have been sampled for water-

quality analyses and flow rates since fall, 1994. Chemical analyses were conducted by a commercial laboratory using standard methods. Flow rates were determined by diverting flows through a 6-in polyvinyl chloride (PVC) pipe and measuring amounts captured in a bucket during a time measured by stopwatch. Flow measurements were made at least in triplicate and the results averaged. The October 2, 1995, data is shown in Table 1 and represents typical water quality data for the surface inflows.

Results

Determining whether or not the coal seam is inundated is a very important aspect of the site. The mine floor in well 21 is at an elevation of 281.16 meters (922.45 feet), the water table is at approximately 283.51 meters (930.15 feet), and with a relatively flat coal seam and a thickness of 1.22 meters, it can be assumed that the underground mine is completely flooded. The direction of flow is towards Pond G, located at the base of a highwall 15 to 23 meters (50 to 75) feet north of the well (Figure 1). Pond G has an average water elevation of 281.7 meters (924.1 feet). So, there is about 1.8 meters (6 feet) of head driving the water from the old underground mine voids towards Pond G.

Mine maps showed possible auger mining northeast of well 2 and adjacent to Pond J. Well drilling penetrated an auger opening in the highwall above well 2, and a 2-inch observation well was placed there (well 4). The well is 32.6 meters (107 feet) deep and rests on top of the underclay. The auger-mining void was completely flooded. The water level was 286.6 meters (940.4 feet) and the water level in well 2 was 284.0 meters (932.0 feet), which indicates that the auger-mining voids are a source of recharge for the coal-cleaning waste pit.

Several attempts were made to intercept auger openings in the highwall above Pond J. Every attempt resulted in hitting unmined coal. One well, well 19, was left in and surveyed to obtain water-level

Table 1. Water-Quality and Flowrates for Flows into and out of Howard Williams Lake for October 2, 1995.

Location	pH	Total Acidity (mg/L as CaCO3)	Sulfate (mg/L)	Total Iron (mg/L)	Total Manganese (mg/L)	Aluminum (mg/L)	Flowrate (gpm)	Influx of Acidity (kg/day)
ALD Spring	2.93	1672	3860	600	79	60	6.5	53.9
ALD Stream	2.95	1394	3081	460	60	69	2.5	17.2
Standpipe	5.61	-22	3068	520	60	1	1.7	-0.2
Spring W	3.00	368	2140	106	44	15	4.9	8.9
Spring I	3.95	790	3002	417	64	23	1.2	4.6
Spring U	4.15	227	1288	83	25	13	83.5	94.7
Stream W	7.60	-106	230	<1	<1	<1	33.7	-17.8
Spring N	3.00	1093	2800	235	37	48	<.5	0
Stream G	6.02	-19	453	12	2	2	59.3	-5.6
Spring G	3.15	250	1255	76	19	18	18.4	22.9
Stream J	2.78	418	1473	54	31	17	21.4	44.7
Outlet	3.00	305	1236	24	23	13	234	357

elevations. The water level in well 19 is around 279.3 meters (916.2 feet) and Pond J is 278.1 meters (912.4 feet). So the strip ponds to the south of Howard Williams Lake are receiving recharge from the unmined coal seam and auger openings. This connection was verified with a qualitative tracer test using fluorescein dye. A positive result was obtained in Pond J within a week of dye injection into well 19.

Two more wells were installed in areas to the northwest of Howard Williams Lake that are thought to be affected by underground mining. Wells 22 and 28 are located above Pond A and B. Water level elevations for well 22 and 28 are 285.9 and 284.1 meters (938.0 and 932.0 feet), respectively. Both of these wells have about 16 feet of water above the underclay, thus the coal seem is also completely submerged in this area. No underground mine rooms were intercepted with these wells, but rooms do exist in the area according to the mine maps.

The remainder of the wells were placed in the strip mine areas around the lake. Wells 1, 2, 2A, 2C, and 3 are all in an old strip pit occupied by coal-cleaning waste. The mine waste has a thickness of about 18 meters (60 feet), with the bottom 5 to 6 meters (15 to 20 feet) being submerged. According to water-level elevations, the water in the pit tends to move to the southeast towards Howard Williams Lake. It may be possible that the water in this pit is seeping out at the seeps near the anoxic limestone drain (ALD).

Wells 13, 14, 15, 16, 17, and 35, are all in the unreclaimed spoil areas to the south and west of Howard Williams Lake. All of these wells are very shallow and are located near the base of the spoil piles. Wells 10 and 12 are also shallow wells, but have been placed in the reclaimed spoil areas. Well 10 is near Pond A and well 12 is within 100 feet of the north shore of Howard Williams Lake. Wells 5, 5A, 5B, and 6A are located to the southwest of the coal-cleaning waste pit in the reclaimed spoil.

Water Budget

There are several surface inflows into Howard Williams Lake. The quality and quantity of these inflows vary considerably. The lake discharges through a drop-inlet in the southeastern side of the lake. The drop-inlet then drains into a 122 centimeter (4 feet) diameter concrete pipe which passes through the dam and drains to the east of the lake. Flowrate measurements for the outlet of the lake have been done using Manning's equation, since normal flow exists in the pipe (Chow, 1959). By using Manning's equation, the only field measurement needed is the width of flow. The pipe has a slope of 0.026 m/m, diameter of 122 centimeters (48 inches), and the Manning's roughness coefficient has been estimated at 0.018 for this pipe.

All of the surface inflows to the lake were low enough to be measured using a bucket and a stopwatch. At least three trials were done on each inflow to get an average value. The location of the inflows are shown in Figure 1 and the average inflow rates are shown in Table 2. Stream J discharges water from Ponds L, J, and H, and enters the lake through a small culvert underneath an old haul road on the south side of the lake. Seep G is a seep that converges with Stream G and enters the lake though another culvert that runs underneath the haul road on the south side of the lake. Spring U is a seep about 0.3 meters (1 foot) in diameter that is located about 5 meters west of the west edge of the lake and is between the haul

Table 2. Average Flowrates.

Location	Flowrate (gpm)
ALD Spring	4.96
ALD Stream	1.87
Standpipe	1.50
Spring I	2.24
Spring W	5.08
Spring N	0.55
Stream W	27.66
Spring U	76.72
Spring G	19.30
Stream G	79.80
Stream J	27.79
Outlet	295.00

road and the lake. Stream NW has two forks - the west fork is runoff from Pond B, Spring N is fed by a seep coming out of the reclaimed spoil created by the reclamation to the north. Both forks flow through a limestone-lined channel installed during reclamation. Spring W, Spring I, Spring N, ALD Stream drain seeps originating in reclaimed spoil north of the lake and flow through limestone-lined channels installed during the reclamation. ALD Spring and ALD Stream, which drain seeps, are adjacent to an anoxic limestone drain that drains out a standpipe located near the shore of the lake. The streams are all located in swales created by the reclamation. The limestone channels are heavily covered with iron oxides. The channels also carry very little surface runoff and have not shown any scouring effects during storm events.

Water-Quality

Water sampling began in the fall of 1994 and has continued through 1995. Initially only the surface inflows to, and outflows from, Howard Williams Lake were sampled. This was expanded to include all of the monitoring wells as they were installed throughout the site. The goal of the water-quality analysis is to determine the areas around Howard Williams Lake that are contributing to the poor water-quality conditions found in the lake, so that an economical and effective restoration plan can be designed.

All inflows and outflows have been sampled several times over the last year and a half. Attempts were made to sample during wet and dry periods to see what effect rainfall had on water-quality and flow. A few sample sets were taken after rainfall events, but most of the sample sets were primarily taken during low flow periods. After rainfall events, flowrates of streams connected to ponds increased while their acidity decreased. Springs had no noticeable change in flowrate or quality.

Discussion

From Table 1 it can be seen that the major sources of acid mine drainage are ALD Spring and Spring U. These two sources of water account for only 32% percent of the surface flow entering the lake, but contribute 63% of the acidity.

ALD Spring is believed to be the result of recharge entering the spoil and flowing through zones of high pyritic content. A gob pit to the northwest of ALD Spring and underneath wells 1, 2, and 3, has been proven to be in direct connection to ALD Spring by using particle tracking in Visual Modflow (Guiguer and Franz, 1996).

The source of water for Spring U is Pond G, which is believed to be connected to an underground mine opening. Pond G is at an elevation of 281.7 meters (927.69 feet), while Howard Williams Lake is at 278.5 meters (913.8 feet). Pond G is separated from Howard Williams Lake by a spoil pile. Stream G carries water from Pond G over a series of

beaver dams and into Howard Williams Lake through a culvert. The beaver G and the lake. The large difference in head between these two bodies of water is believed to be the driving force behind two seeps, Seep G and Spring U, that exit the spoil pile at or near the elevation of the lake. The seeps are believed to be the result of pseudokarstic conditions typical of mine spoil (Aljoe, 1994). Table 3 shows how the water-quality changes as it goes from the underground mine rooms through the highwall into Pond G and eventually into the lake via Stream G and Spring U.

As can be seen from Table 3, the water that seeps through the spoil pile deteriorates substantially before it exits the spoil pile. Acid-base accounting data for the spoil adjacent to Pond G is not known, but core samples from well 21 give a good indication as to the quality of the overburden (Table 4). Well 21 is located about 30 meters from the edge of the highwall that is adjacent to Pond G. Based on stratigraphy from drilling records and tables, well 21 has a height-averaged pyritic sulfur content of 0.24 percent, with a potential acidity of 7.55 g/kg, and a neutralization potential of 0.43 g/kg ($CaCO_3$). These values are representative of the spoil adjacent to Pond G. Sobek *et al* . (1978), defined geologic material as being potentially toxic if the pH is less than 4.0 or the material has a net $CaCO_3$ deficiency of 5 grams or more dams have created a head difference of 5 meters (13.9 feet) between Pond per kilogram of material. For well 21, the only material that is considered potentially toxic is the Freeport Coal, but this seam is very shallow and often non-existent in the highwalls. The gray sandstone, which makes up a good portion of the overburden, can be considered potentially toxic due to its $CaCO_3$ deficiency, but not its pH. Pyrite contents are not particularly high, but result in toxicity due to a general lack of alkalinity in the overburden.

Stream J is another major source of acid mine drainage. Pond H and L overflow into Pond J, which drains out Stream J to Howard Williams Lake. There are two sources of recharge to these ponds: spoil groundwater and the highwalls. A connection exists between the highwall and Pond J, as proven recently with a tracer test. However, adjacent spoil is the major cause of poor water-quality in Pond H, J, and L. By comparing water-quality data for Stream J, well 17 (in spoil) near Stream J, and well 19 (highwall), the water-quality of Pond J is related to the water-quality in the spoil. The percentage of water that each source contributes to Pond H, J, and L is not clear at this time. The quality of the overburden was obtained from acid-base accounting data for well 21. The height-averaged pyritic sulfur content is 0.24 percent with a potential acidity of 7.55 and

Table 3. Effects of Spoil on Typical Water Quality from Well 21A to Spring U

Location	Head (ft)	pH	Total Acidity (mg/L as CaCO3)	Sulfate (mg/L)	Total Iron (mg/L)	Manganese (mg/L)	Aluminum (mg/L)
Well 21A	929.7	6.18	-4.67	266	19	2.02	0.69
Pond G	927.7	6.66	-48.50	95	1	0.90	0.10
Stream G	922.1	4.94	32	492	15	4.43	3.08
Spring G	915.2	3.27	308	1401	79	25	21
Spring U	915.2	3.98	419	1438	82	28	15

Table 4. Acid Base Accounting Data

Location	Depth (m BGS)	pH	Material	Neutralization Potential ton/kton as CaCO3	Total Sulfur (%)	Pyritic Sulfur (%)	Potential Acidity total sulfur*	Potential Acidity pyritic sulfur*	CaCO3 Deficiency total sulfur*	CaCO3 Deficiency pyritic sulfur*
Well 3	4.6	2.87	Gob	-2.35	6.60	4.94	206.3	154.4	208.6	156.7
Well 3	9.1	3.39	Gob	-1.05	6.00	4.82	187.5	150.6	188.6	151.7
Well 3	10.7	4.27	Gob	3.67	4.81	3.90	150.3	121.9	146.6	118.2
Well 3	13.7	4.35	Gob	4.40	10.75	8.61	335.9	269.1	331.5	264.7
Well 3	18.3	4.06	Gob	-2.87	4.72	3.10	147.5	96.9	150.4	99.7
Well 3	22.3	3.41	Gob	-0.20	1.37	1.03	42.8	32.2	43.0	32.4
Well 5	3.0	4.10	Spoil	0.50	0.24	0.06	7.5	1.9	7.0	1.4
Well 5	6.1	4.23	Spoil	-0.25	0.50	0.36	15.6	11.3	15.9	11.5
Well 5	12.2	4.35	Spoil	-0.25	0.29	0.24	9.1	7.5	9.3	7.8
Well 5B	5.5	3.61	Spoil	-2.00	0.40	0.03	12.5	0.9	14.5	2.9
Well 6	9.1	5.38	Spoil	9.99	0.60	0.53	18.8	16.6	8.8	6.6
Well 6	12.2	4.82	Spoil	10.70	0.86	0.80	26.9	25.0	16.2	14.3
Well 6	18.3	2.10	Spoil	-75.70	20.00	11.50	625.0	359.4	700.7	435.1
Well 6	18.6	2.67	Spoil	-9.74	3.26	2.07	101.9	64.7	111.6	74.4
Well 6	19.5	5.10	Spoil	0.50	1.02	0.98	31.9	30.6	31.4	30.1
Well 10	6.1	4.91	Spoil	2.25	0.30	0.07	9.4	2.2	7.1	-0.1
Well 10	9.1	3.43	Spoil	-75.70	2.00	1.23	62.5	38.4	138.2	114.1
Well 19	13.1	5.99	WSS	4.40	0.01	0.01	0.3	0.3	-4.1	-4.1
Well 19	22.3	6.85	WSS	6.10	0.34	0.33	10.6	10.3	4.5	4.2
Well 19	25.3	6.59	USS	24.20	0.27	0.26	8.4	8.1	-15.8	-16.1
Well 19	28.3	5.68	USS	19.50	1.29	0.57	40.3	17.8	20.8	-1.7
Well 19	31.4	5.39	Shale	12.90	1.87	1.32	58.4	41.3	45.5	28.4
Well 19	32.9	6.50	Shale	11.00	1.48	0.80	46.3	25.0	35.3	14.0
Well 19	34.7	3.52	Coal (K)	-3.75	4.00	2.18	125.0	68.1	128.8	71.9
Well 21	7.6	5.21	Shale	22.00	0.36	0.36	11.3	11.3	-10.8	-10.8
Well 21	8.8	3.10	Coal (F)	-27.50	8.36	6.31	261.3	197.2	288.8	224.7
Well 21	11.0	5.59	USS	0.80	0.30	0.30	9.4	9.4	8.6	8.6
Well 21	22.3	6.16	WSS	0.57	0.01	0.01	0.3	0.3	-0.3	-0.3
Well 21	25.3	5.75	USS	-0.27	0.57	0.57	17.8	17.8	18.1	18.1

BGS = Below Ground Surface
WSS = Weathered Sandstone
USS = Unweathered Sandstone
F = Upper Freeport No. 7 Coal
K = Middle Kittanning No. 6 Coal
* units = ton / 1000 tons as CaCO3

neutralization potential of 0.43 g/kg ($CaCO_3$). That well 19 (thus the highwalls) has good water while spoil groundwater is bad indicates oxidizing conditions in the spoil.

Using the MODFLOW computer program (McDonald *et al* ., 1988), the recharge for the spoil surrounding Pond J, H, and L that is required to match the seasonal flowrate recorded at Stream J (1.6 L/s), is 0.60 cm per year, which is relatively low. This may result, in part, from the steep slopes of the spoil piles and the lack of good vegetation. The highwall was not considered a source of water; it was modeled as a no-flow boundary. The haul road between the lake and the ponds was also considered a no-flow boundary because it is less than 3 meters above the elevation of the underclay and greatly compacted.

One of the most interesting aspects of this site is the water-quality in strip ponds to the west of Pond G (Table 5). All of the water to the west and northwest of Pond G is of good quality water. The strip mining done in these areas was done at the same time as the mining around Pond G, H, J, and L. As you go to the west of Spring U the water-quality improves. One possible reason is that there is a lithologie change from west to east. We have been unable to determine if limestone is present in the overburden to the west of Howard Williams Lake. Well logs from wells 22 and 28 show no evidence of any alkaline material. Another possible reason is that Pond A, B, and F are much deeper than Pond H, J, and L. On average, Pond A, B, F, and G contain 4 to 9 meters (15 to 30 feet) of water above the underclay. Pond H, J, and L are much shallower with depths of only 4 to 10 feet. The deep ponds are able to submerge the pyritic roof shale of the exposed highwall, while the water level in the shallow ponds fluctuate within the roof-shale zone, resulting in greater acid production in the shallow ponds.

The topography of the reclaimed spoil on the north side of the lake is substantially different than the undisturbed spoil to the south and west. The most noticeable difference is the lack of any significant inflows into the lake. The reclamation eliminated all of the strip ponds, thus it also eliminated the possibility that beavers would dam up a flow, creating a situation similar to Pond G, where increased head increased the amount of water flowing through potentially toxic spoil. The north side only contributes about 25 percent of the flow that enters Howard Williams Lake, but contributes a more significant amount of chemical load due to much higher concentrations of sulfate, iron, manganese, aluminum, and various other metals.

The effects that the coal-cleaning waste pit has on lake-water quality has not been clearly defined. Wells 1, 2, 2A, 2C, and 3 are all screened within the pit and are shown on the map in Figure 1. The water-quality data for these wells are

Table 5. Typical Water Quality of Ponds West of Howard Williams Lake

Location	pH	Total Acidity (mg/L as CaCO3)	Sulfate (mg/L)	Total Iron (mg/L)	Manganese (mg/L)	Aluminum (mg/L)
Pond A	6.51	5.0	240	0.47	2.12	0.38
Pond B	7.10	-34	223	0.27	0.55	0.30
Pond F	6.83	-17.5	198	0.50	0.47	0.49

Table 6. Typical Water Quality of Wells Located in Gob Pit.

Location	pH (field)	Total Acidity (mg/L as CaCO3)	Sulfate (mg/L)	Total Iron (mg/L)	Manganese (mg/L)	Aluminum (mg/L)	Total Hardness (mg/L)
Well 1	3.55	437	1317	244	16	4.1	1144
Well 2	4.91	345	1310	215	11	0.6	1025
Well 2A	4.52	856	2800	1160	22	21.6	1913
Well 2C	5.13	334	3382	299	12	4.6	1949
Well 3	3.56	197	791	112	4	7.0	493

shown in Table 6. Though the field pH is high in wells 2 and 2C, upon oxidation the pH drops to 3.0 resulting in the hot peroxide acidities shown in the table. Acid-base accounting data for well 3, shown in Table 4, show very high pyritic sulfur contents and $CaCO_3$ deficiencies. From the water-quality data, the mine waste appears to be very heterogeneous, with some areas producing more acidity than others.

Wells 5, 6, 10, and 12 are located in reclaimed spoil north of Howard Williams Lake. Water-quality data, shown in Table 7, show acidic conditions in wells 5, 6A, 10, and 12, with varying degrees of acidity. This is another example of heterogeneous conditions within a spoil pile. Acid-base accounting information for wells 5, 5B, 6A, and 10, also show very heterogeneous conditions, with some samples being marginally toxic, while other samples

Table 7. Well Water Quality Data for October 2, 1995.

Location	pH	Total Acidity (mg/L as CaCO3)	Sulfate (mg/L)	Total Iron (mg/L)	Manganese (mg/L)	Aluminum (mg/L)	Hardness (mg/L)
Well A8	3.21	1709	3800	720	83	90	2316
Well 2	5.20	-12	1129	214	9.3	0.6	872
Well 2C	5.85	-55	3671	310	10.8	0.1	1716
Well 3	3.15	176	727	120	4.5	29	120
Well 4	3.19	124	851	97	4.2	0.5	589
Well 5	3.09	523	2245	267	51	20	1768
Well 5B	4.51	237	2335	196	30	0.1	2126
Well 6A	5.10	521	1800	303	32	0.2	1410
Well 10	5.43	187	1893	262	52	0.2	1916
Well 12	3.68	227	3071	296	107	22	2516
Well 13	3.18	1783	4987	276	78	280	2947
Well 14	3.88	178	665	89	20	2	599
Well 17	3.05	970	3323	280	68	84	2253
Well 19	6.68	-127	482	0.81	2.5	0.1	453
Well 21A	6.35	-91	356	27	1.02	0.2	473
Well 22	5.30	-14	43	0.54	0.53	0.2	326
Well 28	7.02	-197	119	0.91	0.27	0.1	316
Well 35	5.92	-105	897	40	44	0.5	1168

are extremely toxic.

To this point, direct groundwater contributions to the lake have not been discussed. According to mine maps, the elevation of the underclay is above the lake surface. This make sense due to the number of seeps that exit the spoil several feet above the lake surface. Several water budget calculations have been made and are shown in Table 7. On average, surface inlfows contribute a high percentage of the lake outflow, the differences being subsurface flows and evaporation from the lake surface.

The anoxic limestone drain (ALD), located between ALD Spring and ALD Stream has been effective in treating groundwater that would eventually enter the lake. The water-quality characteristics of the water going into and exiting the anoxic limestone drain are shown in Table 9. The drain was built in 1990 and has a flowrate of about 2 gpm. There is no stabilization pond collecting the water that drains from the ALD, the water drains directly into Howard Williams Lake. It is interesting to note the amount of aluminum being taken out by the ALD, therefore at some point in the future it may show signs of clogging up.

Conclusions

The degradation of water-quality in Howard Williams Lake is caused by movement of groundwater through toxic spoil and possibly also by drainage of underground mine voids which are not fully flooded. The source water is recharge from precipitation percolating through spoil, and head differences created by ponds in old pits surrounding the lake. The water-quality in mines which are completely inundated is good, as a result of anoxic conditions. If the water table in the inundated mines is lowered, introduction of air could cause an increase in acid mine drainage

Table 8. Water Budget for Howard Williams Lake

Date:	9/22/94	10/8/94	10/15/94	10/27/94	8/28/95	10/2/95
Inflows (gpm)						
Stream J	27	30	36	28	14	21
Stream G	78	66	73	67	94	59
Spring G	25	19	20	20	19	18
Spring N	0	0	0	0	1	1
Stream W	0	0	0	0	53	34
Spring U	90	69	72	71	84	83
Iron stone seep (east)	0	0	0	0	0	0
Spring I	4	4	4	4	2	1
Spring W	0	0	0	0	7	5
Standpipe	2	0	1	2	2	2
ALD Stream	0	0	0	0	3	2
ALD Spring	3	4	4	4	7	6
Total Inflows	229	194	210	196	284	234
Outflow (gpm)						
Drop-Inlet	295	143	163	143	295	234

Table 9. Performance of Anoxic Limestone Drain.

Anoxic Limestone Drain					
date sampled:	8-Oct-94	5-Nov-94	22-May-95	28-Aug-95	2-Oct-95
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
In					
pH			3	3	3
Total Acidity			905	1414	1709
Aluminum			87	87	90
Out					
pH	5	6	6	6	6
Total Acidity	746	791	882	618	0
Aluminum	2	2	2	1	1

production. Since the No. 6 coal seam averages several percent pyritic sulfur, the coal remaining as pillars and between auger openings may provide a significant source for acid to be produced.

The effect that the coal-cleaning waste pit has on lake Water table elevations show a slight gradient toward the lake, but whether or not this water is directly affecting the water-quality of Howard Williams Lake is not known. Tracer tests and geophysical investigations may be able to define what role the coal-cleaning waste has on lake-water-quality. Likewise, the actual contribution to lake acidity from spoil piles surrounding the lake in not yet well defined. Water-quality data and acid-base accounting data show the heterogeneous conditions throughout the spoil area.

Data clearly show regional differences in water-quality surrounding the lake. Local sportsmen routinely fish in ponds west of the lake; unfortunately these high quality ponds contribute very little flow to the lake. Complete surveys of pond depths, correlated with adjacent coal-seam elevations should confirm the extent to which mined-out subsurface areas are flooded, and to what depths. Underclay elevation data suggest very localized variations in topography which could provide preferential flow paths in partially flooded underground mine rooms. Ponds as much as 25-feet deep may be creating anoxic conditions in both the mined-out subsurface as well as several feet upward into roof shales and pyritic sandstones. Other studies in Appalachian mining regions have shown that coal-seam roof rock may be more pyrite-rich than super-jacent or subjacent strata, and thus a greater source of acidity.

Our investigations ultimately will provide data upon which a sound and effective engineering design to re-route waters affecting the lake can be based. This design may well include some classical treatment options; but control of flows within the entire watershed appears also to have a high probability of effectiveness. A future use of this lake is proposed for recreation purposes, so that consideration of all related waters in the region is highly desirable.

Acknowledgements

This work has been supported, in part, by the Ohio Department of Natural Resources, Division of Reclamation.

Literature Cited

Chow, Ven Te. 1959. Open Channel Hydraulics. McGraw-Hill, Inc., New York, p. 98-114.

Dickinson, S. K. 1986. Use of Papermill/Sewage Sludge and Composted Sludge in Mineland Revegetation. *In*, New Horizons for Mined Land Reclamation, American Society for Surface Mining and Reclamation (Jackson, Mississippi, March 17-20, 1986), p. 61-64.

Donovan, Joseph J. and Paul F. Ziemkiewicz. 1994. Early Weathering Behavior of Pyritic Coal Spoil Piles Interstratified with Chemical Amendments: Part 1 Mine Drainage. *In*, International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), p. 119-128.

Edwards, Kenneth B. and Walter E. Grube, Jr. 1995. Sources of Greatest Acidity in a Coal-Mined Watershed. *In*, Watershed Management Planning for the 21st Century, Watershed Management Committee of the Water Resources Engineering Division/ASCE (San Antonio, Texas, August 14-16, 1995) p. 175-184.

Guiguer, Nilson and Thomas Franz Visual Modflow version 1.5, Waterloo Hydrogeologic Software, Waterloo, Ontario, Canada, January 1996.

Hawkins, Jay W. and William W. Aljoe. 1992. Pseudokarstic Groundwater Hydrologic Characteristics of a Mine Spoil Aquifer. Mine Water and the Environment 11(2): p. 47-68.

Hedin, Robert S. and George R. Watzlaf. 1994. The Effects of Anoxic Limestone Drains on Mine Water Chemistry: Part 1 Mine Drainage. *In*, International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), p. 185-194.

Lapakko, Kim A. 1994. Evaluation of Neutralization Potential for Metal Mine Waste and a Proposed Alternative: Part 1 Mine Drainage. *In*, International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), p. 129-137.

McDonald, Michael G. and Arlen W. Harbaugh. 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. Water Resources Investigations, Book 6, Chap. A1, 586p.

Sobek, Andrew A., William A. Schuller, John R. Freeman, and Richard M. Smith. 1978. Field and Laboratory Methods Applicable to Overburdens and Minesoils. U.S. Environmental Protection Agency, Cincinnati, OH, EPA 600/2-78-054.

White, William W., Edward M. Trujillo, and Cheng-Kuo Lin, 1994. Chemical Predictive Modeling of Acid Mine Drainage from Waste Rock: Model Development and Comparsion of Modeled Output to Experimental Data: Part 1 Mine Drainage. *In*, International Land

Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), p. 157-166.

GROUND- AND SURFACE-WATER INTERACTIONS INVOLVING AN ABANDONED UNDERGROUND COAL MINE IN PIKE COUNTY, INDIANA[1]

by

Denver Harper[2], Greg A. Olyphant[3], and Donald R. Sjogren[4]

Abstract. Several highwall pits of an abandoned surface mine in the Springfield Coal Member (Pennsylvanian) are currently occupied by ponds with a total area of approximately 2.3 x 10^4 m^2. These ponds are adjacent to an abandoned underground mine (Patoka Valley Coal and Coke Company No. 1 Mine) in the same coalbed. The mine underlies about 0.3 km^2 and contains approximately 4 x 10^5 m^3 of flooded voids. Monitoring of water levels in wells that are screened in the mine and of the levels of adjacent ponds reveal that average hourly levels vary in unison across a range of less than one meter. The mean potentiometric level of the mine-aquifer, the neighboring ponds, and an artesian spring that issues through the outcrop of the coalbed, are at elevations of about 163 m above sea level. Long-term monitoring and a field experiment that involved pumping of a pond indicated that the mine was connected to two of the ponds and served to recharge, rather than discharge, the ponds. The monitoring and field experiment also allowed determination of the mine aquifer's barometric efficiency (0.3) and its storativity (2 x 10^{-3}). A water-balance calculation indicates that the average recharge rate of the mine is about 0.1 mm/day.

Introduction

The presence of flooded underground workings has profound effects on the hydrology of coal-mining districts because they represent large reservoirs of free-flowing, chemically altered water that may percolate vertically and exfiltrate laterally. In areas that have been subjected to both surface and underground mining, the potential for interactions between surface waters and groundwater is greater than in areas undisturbed by mining: (1) surface-mine highwall pits may abut workings of abandoned underground mines, (2) overburden above underground mines may be fractured, thereby increasing vertical percolation and recharge of voids, and (3) springs which are fed by flooded underground workings may discharge through the coalbed's crop or through mine entrances. Estimates are needed of the hydraulic properties of *mine aquifers*, which we can conceptualize as being comprised of fully flooded underground workings and associated strata in close hydrologic connection. These associated strata would include interior mine pillars, porous and (or) fractured overburden, and surrounding unmined coalbed to an indeterminate distance; in the case of most coalbeds of the Illinois Basin, the presence of relatively impermeable underclays may preclude downward percolation.

As part of background investigations at the Midwestern Reclamation Site in southwestern Indiana, we undertook a program of monitoring and experimentation, in an effort to characterize surface and groundwater interactions. Such characterization is needed in order to identify possible pathways of contaminant movement and other unanticipated hydrologic effects associated with reclamation.

Study Site And Monitoring Installations

The study area is located in Section 22, T. 2S., R. 7W., Pike County, Indiana (fig. 1). It is an upland area situated near the drainage divide between the watersheds of the Patoka River and

[1]Paper presented at the American Society for Surface Mining and Reclamation, Knoxville, TN, May 19-25, 1996.
[2]Denver Harper is Senior Environmental Geologist, Indiana Geological Survey, 611 N. Walnut Grove, Bloomington, IN 47405.
[3]Greg A. Olyphant is Associate Professor of Geological Sciences, Indiana University, Bloomington, IN 47405.
[4]Don R. Sjogren is a graduate student in the Department of Geological Sciences, Indiana University, Bloomington, IN 47405.

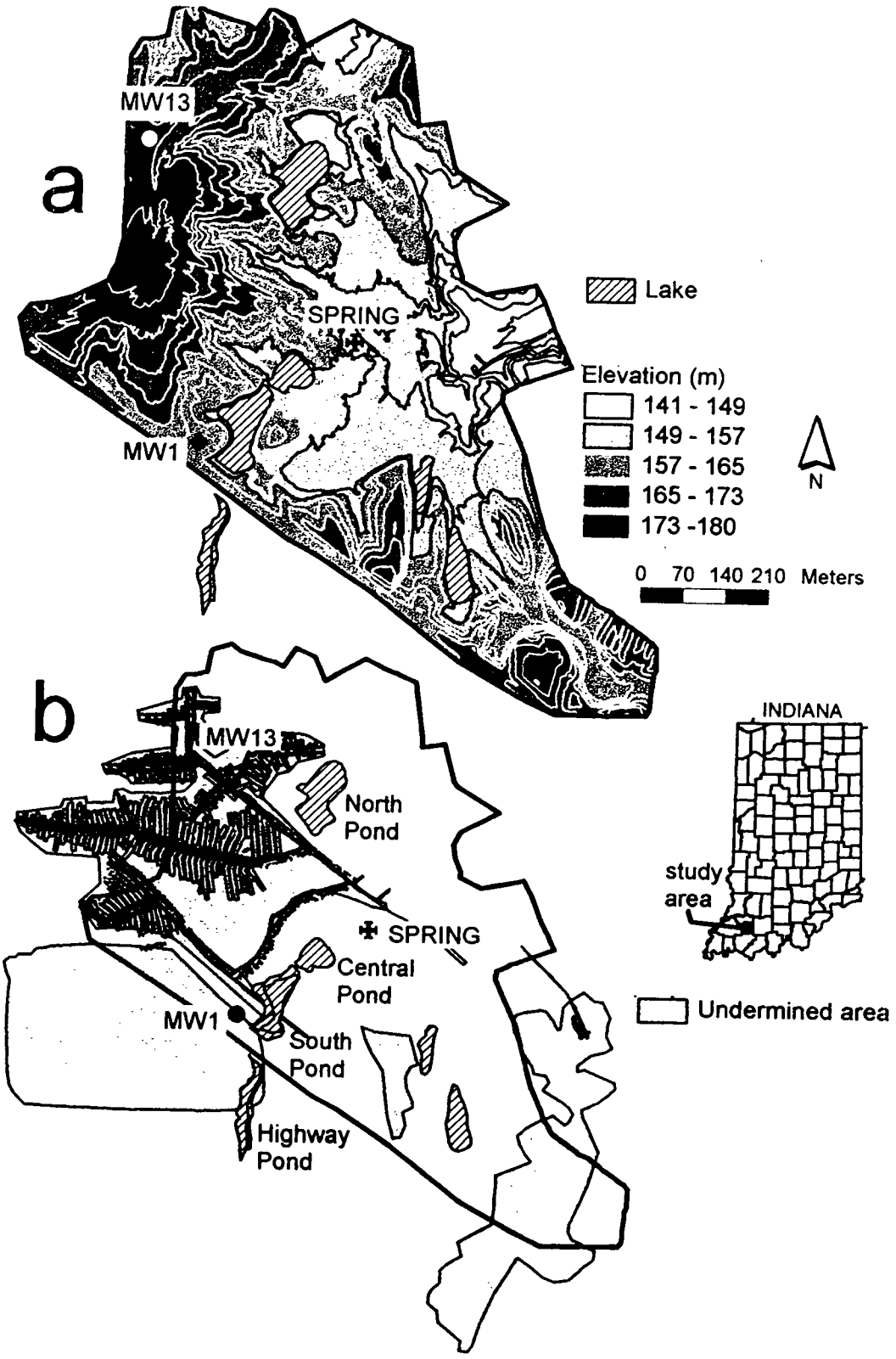


Figure 1. Maps showing (a) surface topography and (b) extent of underground mines and locations of ponds. Locations of monitoring wells and a spring are also shown.

the South Fork of the Patoka River. Much of the surrounding area has been disturbed by surface mining. Three small underground mines underlie parts of the study area at depths of about 30 m or less. As many as eight slopes and shafts formerly existed. In places, the surface mines encountered these abandoned underground workings. Mining was conducted in the Springfield Coal Member (Pennsylvanian).

Figure 1a shows the topography of the reclamation site and Figure 1b shows the portion of the reclamation site and adjacent areas that are underlain by abandoned underground workings. The abandoned Patoka Valley Coal and Coke Co. No. 1 Mine underlies the western part of the reclamation site. There is a map that shows details of the workings in the northern part of this mine (see fig. 1b), but no such detailed map exists for the southern part; the two parts may be separated by a long barrier pillar.

Four surface-mine highwall pits, now filled with water and referred to as the *North, Central, South,* and *Highway Ponds,* are situated along the eastern margin of the Patoka Valley No. 1 Mine and are in close proximity to the mine's workings (fig. 1b). According to available maps, the South Pond intersects a slope entry, while the Highway Pond intersects the southeastern corner of the mine. Continuous electronic monitoring of water levels was conducted at the North Pond (August 15 to October 12, 1995), the Central Pond (May 25 to October 4, 1995), and the South Pond (October 4 to December 11, 1995). The lake levels were also periodically measured at all four ponds using stage staffs. Reclamation activity, which involves draining the ponds, commenced on October 10, 1995.

A monitoring well (MW13, fig. 1) is located within a small interior pillar within the mine workings, and another monitoring well (MW1) is located within the barrier pillar between the two parts of the mine. The water levels within MW13 and MW1 have been continuously monitored since May 25 and September 13, 1995, respectively. (Note: malfunctioning dataloggers resulted in a loss of data from MW13 between September 13 and October 4 and from MW1 between September 27 and October 4, 1995.)

A perennial spring that issued from an outcrop of the coalbed was the major source of streamflow that discharged from the site during dry periods. This spring was located only about 10 m from a small shallow impoundment whose water level stood about 2 m above the spring. Both the spring and the impoundment were in the vicinity of a former slope entry into the underground mine. As part of a field experiment (described below) the discharge of the spring was continuously monitored using an electronic pressure transducer installed in a stilling well; a stage-discharge rating curve was developed to translate the depth measurements into flows.

Results

Water Levels

At any given time, water levels in the wells and ponds differed from each other by as much as 0.4 m. Because monitoring was conducted from late spring through autumn, water levels exhibited an overall decline, falling from an elevation as high as 163.4 m (above mean sea level) at the beginning of the study to less than 161 m at the end of the period considered in this report (fig. 2). Both the wells and the ponds exhibited rapid water-level rises associated with rainstorms that occurred at the site. During a dry period in August, when there were few water-level perturbations caused by rainstorms, the Central Pond, North Pond, and MW13 declined at similar, yet measurably different, rates (1.45, 1.57, and 1.39 cm per day, respectively).

Figure 3 shows water-level changes in MW13 during a five-day period in mid-August. A daily cycle is superimposed upon the long-term decline that is evident in figure 2; this daily cycle is characterized by two maxima and two minima each day. We have previously observed a similar cycle in another flooded underground mine of southwestern Indiana (Harper and Olyphant, 1992), where we concluded that the cyclicity was caused by atmospheric pressure changes.

Barometric Efficiency

The ratio of changes in water level to changes of atmospheric pressure, when both are expressed in the same units, is

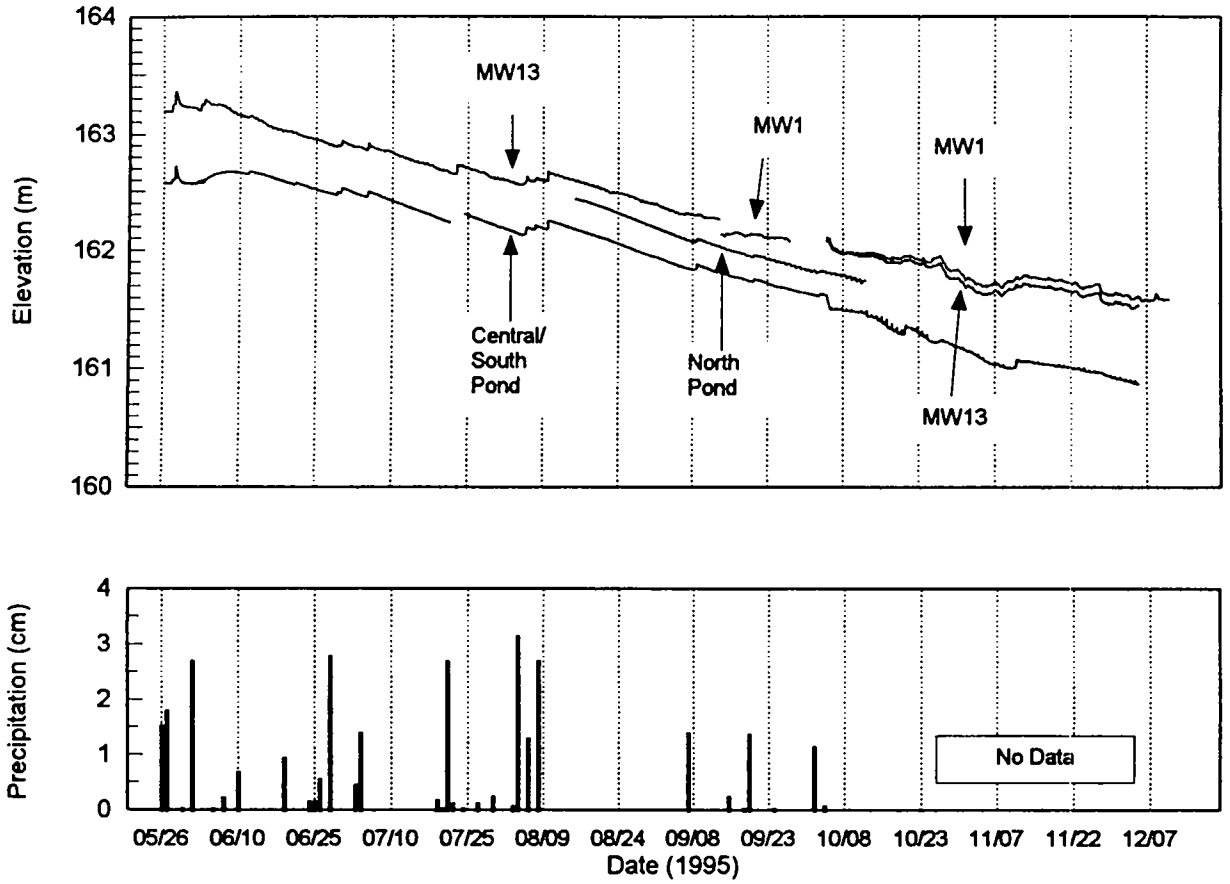


Figure 2. Graphs showing water levels and precipitation during the period of monitoring. Locations of monitoring sites are indicated in figure 1. Vertical grid lines indicate 00:00 AM.

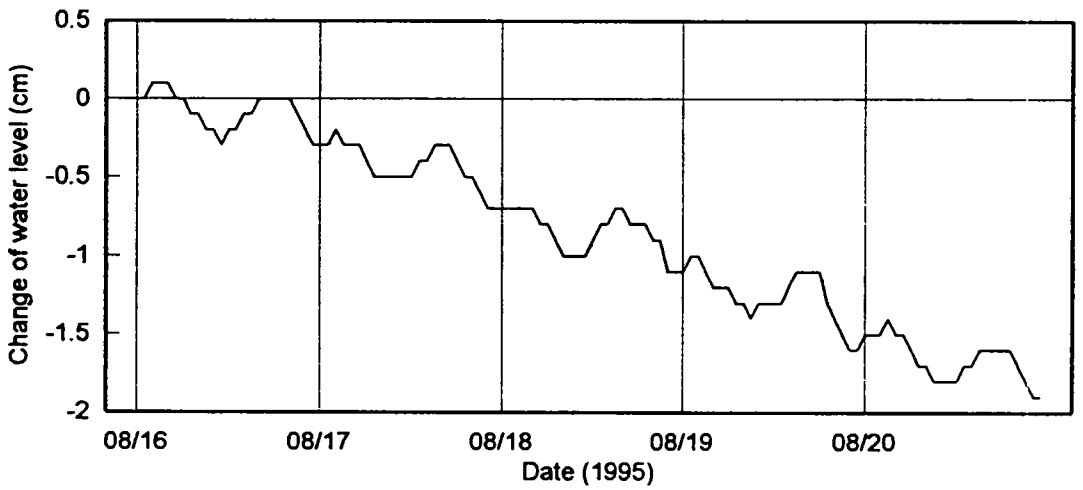


Figure 3. Graph showing daily cycles of water level observed in MW13 during a rainless period in August, 1995. The Y-axis shows the change in water level from its initial value. Vertical grid lines indicate 00:00 AM.

defined as the *barometric efficiency* of a confined aquifer and is related to the aquifer's storativity (Todd, 1959). In Figure 4, daily changes of water level in MW13 are plotted versus daily changes of atmospheric pressure. The overall trend is complicated by variations in water level associated with rainstorms. We employed multiple regression to calculate the partial effect of pressure variations on water-level changes. The statistical results, which are presented in Table 1, indicate that the barometric efficiency of the mine aquifer is 0.31.

Together with information on the thickness and porosity of the mine aquifer, this value of barometric efficiency can be used to estimate the mine aquifer's storativity, according to the following equation:

$$S=\frac{n\gamma b}{EB} \qquad (1)$$

where S is the storage coefficient, n is porosity, γ is the specific weight of water (9800 N/m^3), b is aquifer thickness, E is the bulk modulus of compression of water (approximately 2.07 x 10^9 N/m^2), and B is barometric efficiency. However, considerable uncertainties exist in the estimates of porosity and aquifer thickness in this setting. If we assume that the aquifer consists solely of the flooded mine workings (voids only, and excluding internal pillars), which average 1.4 m in thickness, then the porosity is 1.00 and the value of the storage coefficient is 2 x 10^{-5}. However, if we assume that the aquifer included the sandstone overburden up to the potentiometric level, as well as the mine workings, then the weighted value of porosity is 0.4, the aquifer thickness is 5.5 m, and the value of the storage coefficient is 3 x 10^{-5}. In either case -- given the value of barometric efficiency that we have determined -- the storativity of the mine aquifer lies at the low end of the range (5 x 10^{-3} to 5 x 10^{-5}) given by Freeze and Cherry (1979) for natural confined aquifers.

Field Experiment

On October 4 and 5, 1995, a field experiment was conducted in an effort to quantitatively evaluate interconnection between various ponds, the mine aquifer, and the spring. In order to remove the largest volume of water possible in the shortest period of time, it was decided to pump a lake rather than attempt to pump a well. Because the South Pond is believed to intersect an old slope entrance, it was chosen to be pumped. A volume of 1.5 x 10^6 l was withdrawn in a period of 19.5 hours. During this test, water levels in MW13, MW1, North Pond, South Pond, and the spring were electronically monitored at 15-minute intervals. Stage staff measurements were periodically made at the Central Pond, South Pond, and Highway Pond. Figure 5 shows water-level trends during the experiment, and Table 2 summarizes total water-level and volumetric changes associated with the drawdown.

As shown in figure 5, water levels in the mine (MW13) and the South Pond fell continuously during the period of pumping by about 3.7 and 12.2 cm, respectively, and did not recover in the period immediately following the cessation of pumping. In contrast, the stage of the spring's discharge increased slightly in the early phase of pumping, then declined abruptly about six hours into the experiment, and finally recovered to its preexisting value within a few hours following the end of the experiment. The decline of the spring's stage represents a decrease in its flow rate from 0.5 l/s to 0.1 l/s and a total outflow deficit of 4 m^3 over the period of the experiment.

The difference between the volume of water removed by pumping and the sum of the volumes of water associated with the drawdowns of the Central and Highway Ponds can be used as an estimate of the volume of water lost from the mine aquifer. This estimate, together with data regarding the area of the mine and the observed drawdown in the mine wells, can be used to calculate the storativity of the mine aquifer:

$$S=\frac{\Delta V}{A\Delta h} \qquad (2)$$

where ΔV is the estimate of the volume of water lost from the mine aquifer and A is the area of the mine. Using the data in Table 2, we calculate that the

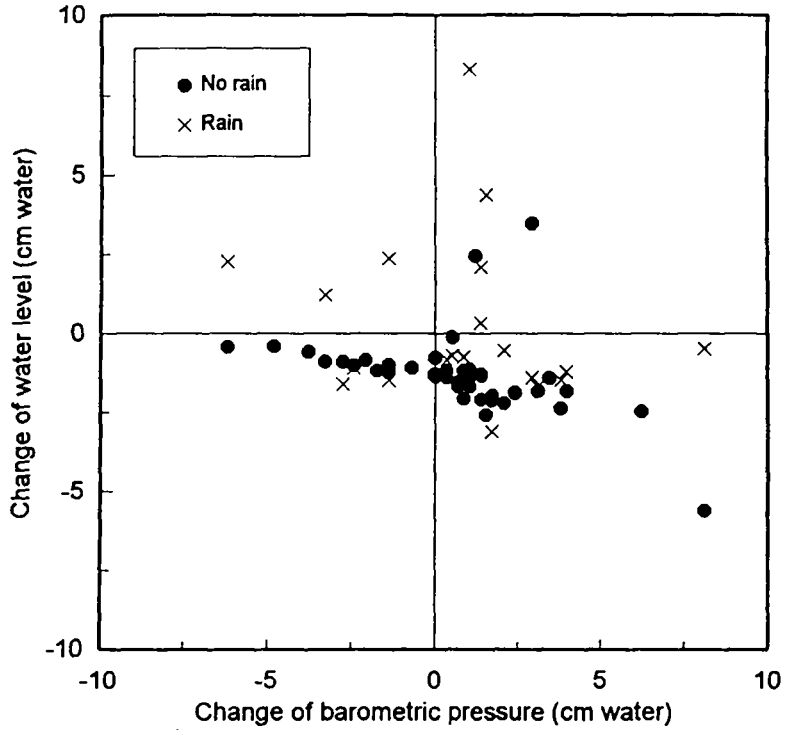


Figure 4. Plot of daily changes in water level of MW13 versus daily changes of atmospheric pressure.

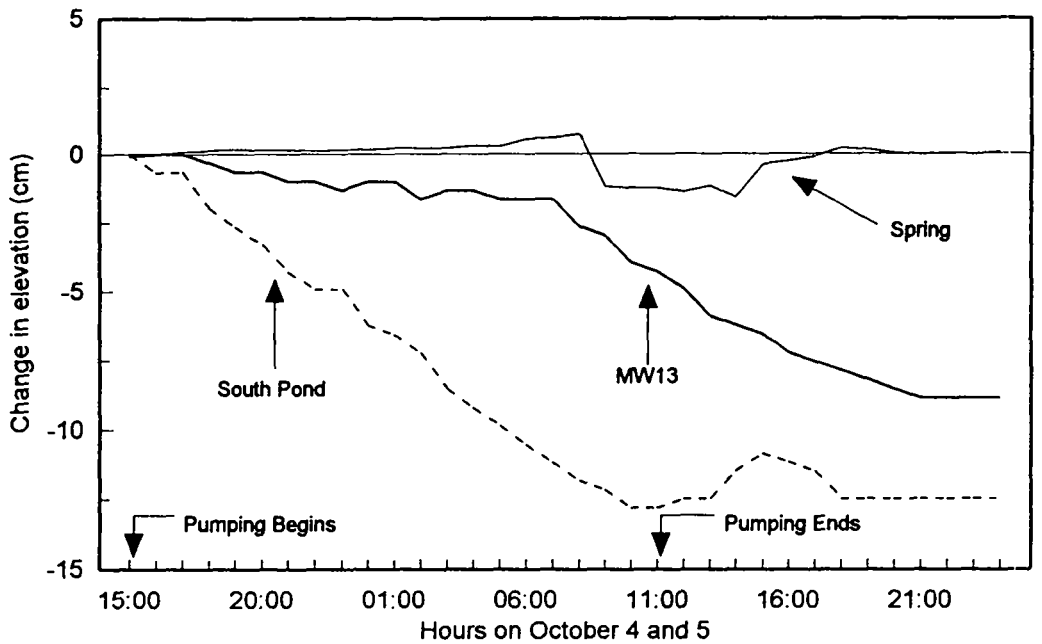


Figure 5. Response of water levels in MW13 and the South Pond during the pump test conducted on October 4 and 5, 1995. The spring's change of stage is also shown.

TABLE 1. Multiple regression analysis of the relationship between changes of the water level in MW13 (Δh), changes of atmospheric pressure (ΔB), and precipitation (P)[1,2,3].

Model: $\Delta h = b_0 + b_1\Delta B_t + b_2 P + (\rho e_{t-1} + v_t)$				
n[4]	b_0	b_1	b_2	ρ
67	-1.356* (0.144)	-0.306* (0.051)	2.050* (0.252)	-0.29

[1]Variables are expressed in centimeters of water.
[2]Regression parameters (b_0 to $_2$ b) and autocorrelation coefficient (ρ) were estimated using the procedure outlined in Kmenta (1971, p. 288).
[3]Values in parentheses are standard errors of regression parameters; asterisks (*) indicate that regression parameters are statistically different from zero at 95-percent confidence level.
[4]n = number of observations;

TABLE 2. Summary of total water-level and volumetric changes associated with pumping of the South Pond. The total volume that was pumped was 1,480 m^3.

Site	Water-level Change (cm)	Area (m^2)	Volume Change (m^3)
SURFACE WATERS			
South Pond	-12.2	6,575	802
Highway Pond	-12	5,460	655
Central Pond	0	not applicable	
North Pond	+0.1		
Spring	---	not applicable	-4[a]
UNDERGROUND MINE			
MW1	-3.7	310,400[b]	27[c]
MW13	-3.7		

[a] Difference between the integrated discharge that was observed (fig. 5) and the discharge that presumably would have been observed if the pump test had not been conducted.
[b] Area includes internal pillars of mine, as well as void spaces.
[c] The volume of water removed from the mine aquifer was determined by subtracting the sum of the volumetric changes given above for the ponds and the spring (1,453 m^3) from the total volume that was pumped (1,480 m^3).

storativity of the mine aquifer is approximately 2 x 10^{-3}. In contrast to our estimate based on barometric efficiency (see discussion above), this estimate lies at the upper end of the range cited by Freeze and Cherry (1979) for natural confined aquifers.

Discussion And Conclusions

Even though available maps indicate that the flooded highwall pits intersected the workings of the abandoned underground mine, the following observations indicate that resistances to flow -- both within the mine workings and between the workings and the ponds -- exist: (1) water levels at all of the sites that were surveyed are at somewhat different elevations at any given time, and (2) although the water levels at different sites show very similar long-term trends, their rates of change are slightly different. On the other hand, both the mine wells and the ponds showed rapid responses to all of the rainstorms that occurred. The higher elevation of the water levels in the mine wells during the period of study (a drying season) indicates that the mine serves as a source of recharge to the ponds and that the mine must be receiving rapid recharge from some other source.

The mine aquifer can be categorized as a *confined aquifer* because its potentiometric level sets high above the roof of the mine. Also, there is no evidence of any conduit connection between the mine and the adjacent ponds. This characterization of the mine aquifer is consistent with the observation of persistent daily cycles of water-level change in the mine and the statistically significant correlation that exists between daily water-level changes and daily atmospheric pressure changes (Table 1). The calculated barometric efficiency of the mine aquifer indicates that this aquifer's storativity is very small (compared with natural aquifers); the field experiment, however, indicates a contrary result. We have conducted similar monitoring (to estimate barometric efficiencies) and field experiments (to determine storativities) at two other sites in southwestern Indiana: at one site, the barometric efficiency was about 0.7 and the storativity was 3 x 10^{-4}, while at the other site, the barometric efficiency was about 0.2 and the storativity was 3 x 10^{-3} (Harper and Olyphant, 1992). These findings were consistent, in that the site with the lower barometric efficiency has the higher storativity. The values obtained in this study -- a low value of barometric efficiency (0.3) and a high value of storativity (2 x 10^{-3}) -- are consistent with the previous results at the other sites and indicate that the mine aquifer at the Midwestern Site is relatively poorly confined. Our results also indicate that values of the storativity of mine aquifers calculated from barometric efficiencies may not be reliable, because of the inherent difficulty of defining the porosity and thickness of such highly heterogeneous aquifers.

Our field experiment indicated the mine aquifer (as monitored in both MW1 and MW13) clearly responded to the drawdown of the South Pond (exhibiting a decline that was seven times greater than the normal daily decline), although the reponse was somewhat delayed and only 30 percent of the decline induced in the South and Highway Ponds. According to our calculation of storativity, only about 27 m^3 of water were lost from the mine aquifer.

The flow discontinuity that occurred near the end of the pump test (and that was coincident with a steepening of the rate of decline of water levels in the mine wells) may be additional evidence that the spring's discharge is derived in part from the mine aquifer. In our calculation of the volume of water lost from the mine, we assumed that the 4 m^3 decrease of spring's discharge associated with the observed reduction of flow was a credit to the mine aquifer's water budget. Even if we disregard the spring's discharge, however, the calculated storativity of the mine aquifer remains on the same order of magnitude.

The data derived from our monitoring program and field experiment have implications for the water budget of the site. For example, the average decline of the water level in MW13 of 1.4 cm/day indicates a net outflow of about 9 m^3/day. However, if we assume that the entire discharge of the spring (ca. 34 m^3/day) is derived from the mine and that other losses probably occur through the mine's connection to the ponds (by

evaporation or exfiltration into adjacent surface-mine spoil deposits) or through exfiltration into adjacent unmined coal, we are in a position to estimate the recharge rate to the mine. If discharge from the mine were solely through the spring, then the recharge rate of the mine would be about 0.1 mm/day; even by doubling the assumed discharge to account for other, unmeasured outflows, the mine's recharge rate must be substantially less than 1 mm/day. This low recharge rate is consistent with characterization of the mine aquifer as a confined aquifer, and indicates that the volumes of water associated with the response of the mine's water level to individual rainstorms is small (< 50 m^3 for rainstorms observed in this study).

Hydrologic conditions in areas where shallow underground workings are in close proximity to surface mines are inherently complicated. Continuous monitoring of water levels can provide information about the responsiveness of various system-components to external stresses and allow inferences about possible pathways of flow between those components. However, such data do not provide direct evidence of connections. Indeed, the variations in water levels that are observed may simply be similar responses to some unmeasured (exogenous) variable. Field experiments -- such as the one described in this report -- where stresses are artificially induced in mine-aquifer systems, provide a more direct basis for qualitative inferences about connections and flow directions, as well as for quantitative determinations of hydraulic properties (*e.g.*, storativity) that can be used in calculations of dynamic water-budgets.

References

Freeze, R. A., and Cherry, J. A. 1979. Groundwater, Prentice-Hall, Inc., Englewood Cliffs, N.J., 604 p.

Harper, D., and Olyphant, G. A. 1992. Requirements of a general operational model for the hydrologic response of flooded room-and-pillar mines to natural and man-made stresses. p. 1 -13. In Proceedings of Fourth Conference on Ground Control for Midwestern U.S. Coal Mines (Mt. Vernon, Ill., November 2-4).

Kmenta, J. J. 1971. Elements of Econometrics, Macmillan, New York, 655 p.

Todd, D. K. 1959. Ground Water Hydrology, John Wiley & Sons, Inc., New York, 336 p.

MODELING THE EFFECTS OF LONGWALL MINING ON THE GROUND WATER SYSTEM[1]

by

R. J. Matetic[2], J. Liu[3], and D. Elsworth[4]

Abstract: The objective of this U.S. Bureau of Mines hydrologic/ subsidence investigation was to evaluate the effects of longwall mining on the local ground water regime through field monitoring and numerical modeling. Field data were obtained from multiple-position borehole extensometers (MPBX's) that were used to measure subsurface displacements. Survey monuments were installed to measure mining-induced surface deformations. Numerous drawdown and recovery tests were performed to characterize hydrologic properties of the overburden strata. Coreholes were drilled above the study area to determine lithologic and strength characteristics of the overburden strata using the rock samples collected. Electronic recorders were installed on all monitoring wells to continuously monitor ground water levels in coordination with mining of the longwall panels. A combined finite element model of the deformation of overlying strata, and it's influence on ground water flow was used to define the change in local and regional water budgets. The predicted effects of the postmining ground water system determined by the model correlated well with field data collected from the field site. Without an infiltration rate added to the model, a static decrease of 3.0 m (10 ft) in water level would occur due to mining of both longwall panels and if an infiltration rate was inputted in the model, no predicted long-term effects would occur to the ground water system.

Introduction

Longwall mining is a method used to extract large blocks of coal. During extraction of the block, the immediate overburden is allowed to collapse, filling the void created by the excavation. Mining-induced strains and displacements are transferred throughout the overburden rock mass due to this collapse and the resultant stress redistribution creates changes to the ground surface and any water-bearing zones located above the mining area. Previous studies have been conducted to delineate the effects of longwall mining on the local ground water system (Booth 1992; Elsworth 1994; Johnson 1992; Leavitt 1992; Matetic 1990; 1991, 1992; Tieman 1992; and Trevits 1991)). Few of these studies, however, have used actual field data, in conjunction with numerical modeling, to determine and

[1]Paper presented at the American Society for Surface Mining and Reclamation 13th Annual Meeting, Knoxville, TN, May 19-25, 1996.
[2]Rudy J. Matetic is a Mining Engineer, Pittsburgh Research Center, U.S. Bureau of Mines, Pittsburgh, PA 15236.
[3]Jishan Liu is a Research Assistant, Pennsylvania State University, Department of Mineral Engineering, University Park, PA,
[4]Derek Elsworth ia a Associate professor, Pennsylvania State University. Department of Mineral Engineering, University Park, PA.

predict mining effects on the ground water regime. The U.S. Bureau of Mines (USBM) is studying the overburden rock mass and its response to high-extraction mining operations through a comprehensive program of field studies. The first part of the work involves the collection of mining, subsidence, overburden response, and hydrological data before, during, and subsequent to mining activity at numerous field sites. The second part of the program is examining methods of predicting the impact to local ground water supplies after mining activity occurs. One of these methods, is through the application of numerical modeling.

Model Approach

An intensive surface, subsurface, and ground water monitoring program was conducted at a mine site in southeastern Ohio. Data collected from this site served as input information for a Finite Element (FE) model. The two-dimensional FE model incorporates the deformation of overlying strata and its influence on ground water flow through applying a simple relationship between mining-induced strains and changes in hydraulic conductivity. The strain field that develops around a longwall panel as a result of mining is caused by material failure and self-weight. From this predicted strain field and from knowledge of the premining hydraulic properties of the overlying strata, the change in hydraulic conductivity that results from the strain field may be determined. With the modified conductivity field determined, the postmining hydrologic system may subsequently be defined through application of a ground water flow model. Again, this ground water model utilizes the finite element method to determine the postmining hydrologic system where the position of the piezometric surface indicates changes in well or aquifer yields. This methodology is used to evaluate the influence of mining on the local ground water regime in this study.

Theoretical Analysis of Modeling Approach

The following assumptions are made when operating the model: (1) the rock matrix is functionally impermeable in comparison with fractures; (2) fluid flow in fractures is defined on the basis of the parallel plate model; (3) changes in fracture conductivity result from changes in normal strains only; (4) strains are partitioned between fractures and matrix as defined by a modulus reduction factor, R_m; and (5) fracture spacing, s, does not change after mining activity (Liu 1994 and Ouyang 1993).

Correlation of Induced Strain and Hydraulic Conductivity

The equivalent porous medium conductivity, K_o, of a rock mass containing a parallel set of fractures can be defined as:

$$K_o = \frac{g}{12\nu_k}\frac{b^3}{s} \qquad (1)$$

where g is gravitational acceleration, ν_k is kinematic viscosity, b is the fracture aperture and s is spacing. R_m, the modulus reduction factor may be defined as:

$$R_m = \frac{E}{E_r} \qquad (2)$$

where E is the deformation modulus of the rock mass and E_r is the deformation modulus of a rock specimen. The modulus reduction factor, R_m, enables the closure across a fracture, Δu_j, to be determined from the difference between the strains in the rock mass and rock speciman as shown below:

$$\Delta u_i = [D + s\,(1 - R_m)]\,\Delta\epsilon \qquad (3)$$

where $\Delta\epsilon$ is the strain in the direction perpendicular to the fracture plane. $\Delta\epsilon$ is positive in extension and negative in compression.

Using the applied strain, $\Delta\epsilon$, from above, the revised conductivity of equation (1) may be defined as:

$$K = R_c K_o \tag{4}$$

where

$$R_c = \left[1 + \frac{b + s(1 - R_m) b^3}{b}\right] \Delta\epsilon \tag{5}$$

Directional conductivities, evaluated from initial conductivities, K_{ox} and K_{oy} (conductivities in the x- and y-directions, respectively) may then be determined from equation (4). With two sets of orthogonal fractures oriented in the x and y directions, the revised directional conductivities may be defined for a two-dimensional system as:

$$= K_{xo} \left[1 + \frac{b + s(1 - R_m)}{b} \Delta\epsilon \right. \tag{6}$$

and

$$= K_{yo} \left[1 + \frac{b + s(1 - R_m)}{b} \Delta\epsilon \right. \tag{7}$$

where K_x and K_y are postmining conductivities in the x-direction and the y-direction, K_{xo} and K_{yo} are the premining conductivities in the x-direction and the y-direction, and $\Delta\epsilon_x$ and $\Delta\epsilon_y$ are the induced strains in the x and y directions, respectively. R_m is a modulus reduction ratio (ratio of mass modulus to intact modulus) that apportions the changes in strain between the fracture and matrix material. When $R_m = 1$, the mass modulus and intact material modulus are identical and the strain is uniformly distributed between fractures and matrix. This results in the smallest possible change in conductivity. When $R_m = 0$, the extensional strain is applied entirely to the fracture system and precipitates the largest possible change in conductivity. These values bound the possible ranges in the behavior of the system in a natural and mechanistically defensible manner. This representation of conductivities is extremely useful, since the modulus-reduction factor, R_m, may be readily evaluated from rock mass classification systems defining structural behavior as a function of readily observable factors of rock structure (Voight 1970). This avoids the difficulty of defining conductivity enhancement in terms of the component moduli of fractures and matrix, parameters that are unlikely to be available in practice. The mining-induced conductivity changes can then be evaluated through equations 6 and 7, provided the mining-induced strain field is determined.

Determination of the Strain Field

The subsidence field that develops around a longwall panel may be determined directly from the FE model. The finite element model applies gravitational load, removes material excavated from the panel and allows the overburden material to fail and deform according to the mining-induced strains. The resulting subsidence field may use the modulus reduction parameter, R_m, to calibrate against field data for a particular site. The insensitivity of the resulting subsidence profile to the material properties of deformation modulus and rock strength parameters, originates from the overriding influence of geometric controls on deformation (Stoner 1983 and Walker 1986). Following mining, the panel span is sufficiently large that closure between panel floor and roof is unavoidable.

Consequently, the resulting strain field, ϵ_x and ϵ_y is defined purely as a function of geometry, as:

$$\epsilon_x, \epsilon_y = f\left[\frac{w}{t}, \frac{w}{h}\right] \qquad (8)$$

where: w represents the width of the panel, t is the thickness of the coalbed and h symbolizes the thickness of the overburden.

The assumption necessary in this evaluation is that strains are uniformly distributed at the scale of a single element. These assumptions seem reasonable where strains are moderate, but may be questionable where significant strain localization occurs.

Determination of the Postmining Ground Water Regime

With the modified conductivity distribution determined from an evaluation of the strain field, and equations (16) and (17), the influence on the postmining ground water regime may be evaluated. The finite element model may determine the influence of a continuously distributed conductivity field (evaluated from the calculated strain distribution) on the ground water budget and water table where boundary conditions are applied to the local system, to represent ground water and surface recharge. Therefore, the change in elevation of the phreatic surface may be determined for the postmining regime. This enables the influence of mining on well yields, aquifer yields, and flow patterns to be identified.

Input Parameters Used for the Modeling Approach

The primary parameters used as input to the model and the measurements obtained from the field are: (1) the initial hydraulic conductivity distribution of the local lithology as determined through field measurements; (2) modulus of elasticity and Poisson Ratio for the rock mass determined from field measurements; (3) the measured subsidence profile; (4) measured vertical displacements; (5) continuous fluid level fluctuations monitored at the site; and 6) flow rates entering the mine after excavation of the longwall panels, as recorded by the operator.

Site Description and Ground Water Monitoring Program

Site Description. The study site is located in southeastern Ohio (Vinton County). The study area overlies a portion of two contiguous longwall panels (Panel Nos. 1 and 2) measuring approximately 300 m (900 ft) wide and 2,950 m (9,000 ft) long (figure 1). The panels were separated by a five entry, four pillar system approximately 120 m (350 ft) wide. The mined coalbed, had an average thickness of 140 cm (55 inches) within the study area. However, the extraction thickness varied between 173 and 183 cm (68 and 72 inches). Overburden thickness was small and ranged from 65 to 85 m (214 to 280 ft). Overall, the strata were fairly level with a regional dip of about 1 degree towards the southeast. There were no major geologic structures and the topography consisted mainly of rolling hills with a maximum relief of approximately 49 m (160 ft).

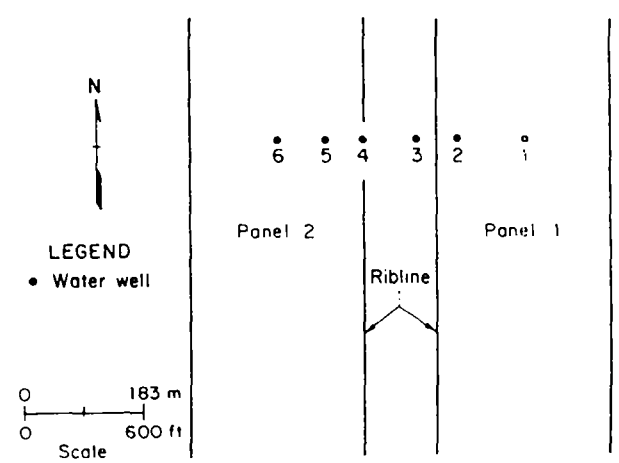


Figure 1. Sketch of study area.

Ground Water Monitoring Program. A total of seven 22-cm (8 5/8-in) diameter monitor wells were drilled for the study. Perforated Schedule 80 (15-cm diameter) (6-in) PVC casing was installed to the total depth in each well to ensure an open wellbore for the life of the study. The wells were strategically placed above both longwall panels as shown in figure 2. The wells were located along a line perpendicular to the trend of the longwall panels. This alignment permitted observations of effects during the mining of both longwall panels. Well Nos. 1 and 6 were located at the center of panel Nos. 1 and 2 respectively. Well Nos. 2 and 5 were located at quarter-panel width. Well No. 3 was located above the gate roads between the two panels and Well No. 4 was located above the edge of panel No. 2. Well No. 7, a control well, was located 427 m (1,400 ft) away from any mining activity.

Data was collected from all wells before, during, and after mining of both longwall panels. Various hydrologic parameters were determined and included specific capacity, transmissivity, hydraulic conductivity, and water level fluctuations. Initial data collection began three months prior to the undermining of Well No. 1 to establish baseline conditions. Drawdown and recovery pumping tests were performed on all wells before and after undermining to determine hydraulic conductivity parameters of the local, shallow geologic units.

Electronic recorders were also installed on all wells to continuously monitor water level fluctuations. The electronic data logger was programmed to record fluid positions every 4 hours.

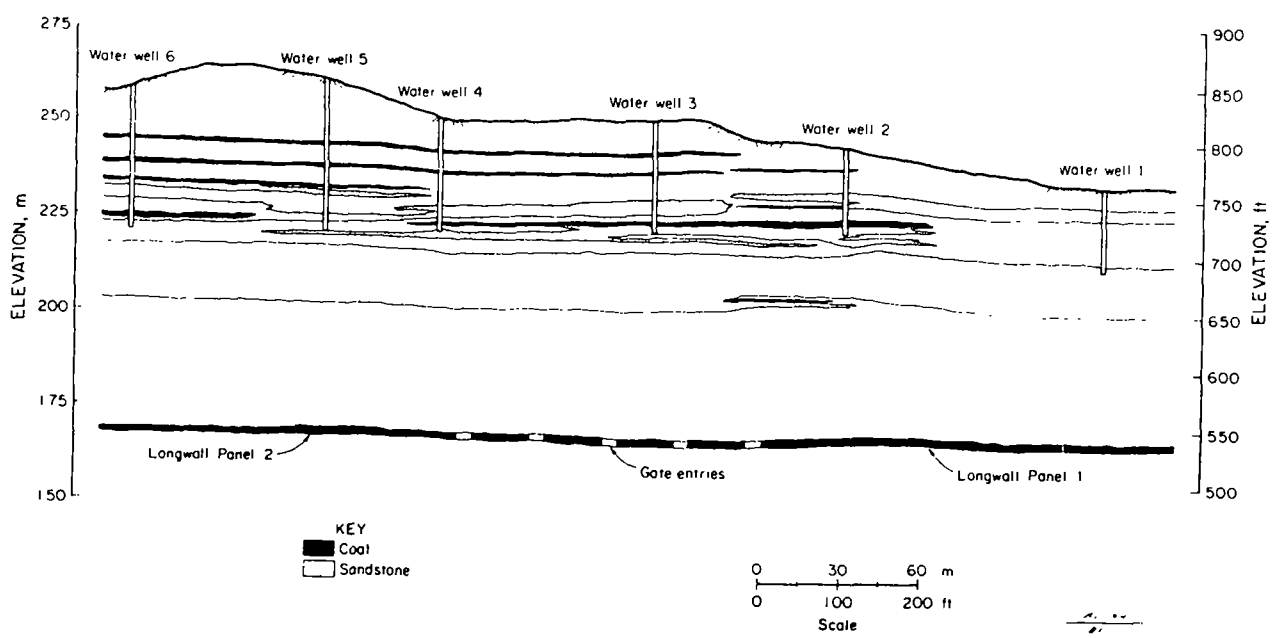


Figure 2. Generalized cross section of study area and Water Well locations

Geology

The geological setting of the study area is typical of that found in southeastern Ohio. The regional dip in this part of the state is to the southeast with the strata striking in a northeast-southwest direction. The average rate of dip is 6 m/km (30 ft/mi). Irregularities to this rate can be experienced by localized thinning or thickening of individual rock units (6). The rock is predominantly interbedded sandstones, shales, thin coal seams and claystones. The individual units are thin (less than 3 m (10 ft) thick) with one sandstone unit having an average thickness of 14 m (45 ft) and lying 43 m (140 ft) above the Clarion 4A Coalbed. To characterize overburden lithology prior to drilling the monitoring wells, six NX-sized coreholes were drilled in the study area to the Clarion 4A Coalbed. Generally, the overburden consisted of about 30% sandstone, 30% shale, 30% claystone, and 10% coal. A generalized cross-section of the study area with the monitor well locations is shown in figure 2.

Modulus of Elasticity and Poisson Ratio Values

The coreholes were drilled above the study area to characterize the local lithology of the overburden and to provide samples for determining geotechnical properties. For input to the model, tests for determining compressive strength, Modulus of Elasticity and Poisson Ratio were conducted on the rock cores collected. Results of tests performed on the core samples showed that the unconfined compressive strength of the major sandstone units are between 2.6×10^4 and 3.0×10^4 kg/m^2 (5,300 to 6,000 psi). Modulus of Elasticity and Poisson Ratio for these units are between 1.3×10^7 to 1.4×10^7 kg/m^2 (2.57 to 2.82×10^6 psi) and 0.30 to 0.32 respectively. A limestone unit, averaging 2.1 m (7 ft) in thickness, is situated about 1 m (3 ft) above the mined coalbed. Testing of core samples show that the unconfined compressive strength of this unit is 1.2×10^5 kg/m^2 (25,000 psi), with a Modulus of Elasticity of 5.1×10^7 kg/m^2 (10.5×10^6 psi), and a Poisson Ratio of 0.28.

Overburden Deformation Monitoring Program

To observe overburden displacement, six 219.1 mm (8-5/8 in) boreholes were drilled along a profile line extending across the two longwall panels. Boreholes 1 and 6 were located in the center of each panel, where the maximum amount of subsidence was expected to occur. Boreholes 2 and 5 were located 30 m (91 ft) from the ribline inside each panel. Borehole 4 was situated 3 m (10 ft) from the ribline (inside the panel) in the expected zone of maximum horizontal tension. Borehole 3 was located in a pillar in the gate entries between the panels to observe the lateral extent of overburden deformation.

Each borehole was outfitted with an eight-anchor multiple-position borehole extensometer (MPBX). Two of the eight anchors in borehole 3 were installed inside a coal pillar to monitor yielding of the pillar. The anchors are numbered 1 to 8, with anchor 1 being the closest to the surface and anchor 8 being the deepest. Figure 3 displays MPBX and anchor locations with respect to the longwall panels.

Subsidence Monitoring Program

To obtain the field subsidence profile, survey monuments were installed on the ground surface and were surveyed regularly to identify the dynamic characteristics of subsidence, the final subsidence profile, and to provide surface reference data for the MPBX units. The monuments were constructed of 1.3 m (4 ft) rebar and

were installed flush to the ground surface. The array of monuments consisted of a baseline (along the centerline) over each panel and a profile line trending perpendicular between the two baselines. The monuments were spaced 15 m (45 ft) apart along the baseline. The profile line was 375 m (1,136 ft) long with monuments spaced 7.5 m (23 ft) apart.

MODEL ANALYSIS

Finite-element Mesh Assemblage

The finite-element mesh construction was assembled utilizing figure 3. The effects of topography, geometry, and lithology were incorporated in the mesh. The mesh utilizes uniform spacing and was constructed of 2,066 nodes and 1,928 elements. The mesh assumes differing materials (overburden material and coal layer) for the determination of strain and displacement characteristics, and three materials (upper shale layer, sandstone layer and lower shale layer) for determination of the postmining flow characteristics within the system. The boundary conditions of the model for determining displacement and strain characteristics assume no horizontal movement on either side of the mesh and no vertical movement on the base. Boundary conditions associated with monitoring postmining ground water effects assume no flow on the bottom of the mesh and constant head conditions on the lateral sides of the mesh. The finite-element model is two-dimensional and determines the strain field with two displacement degrees of freedom applied to each node, and subsequently evaluates the revised flow system using a single degree of freedom. The analyses are coupled through the dependence of hydraulic conductivity on the induced strain field, as defined in equations 6 and 7.

Subsidence Profile

The subsidence profile (figure 4), generated by the model, was determined with the input parameters as shown in table 1.

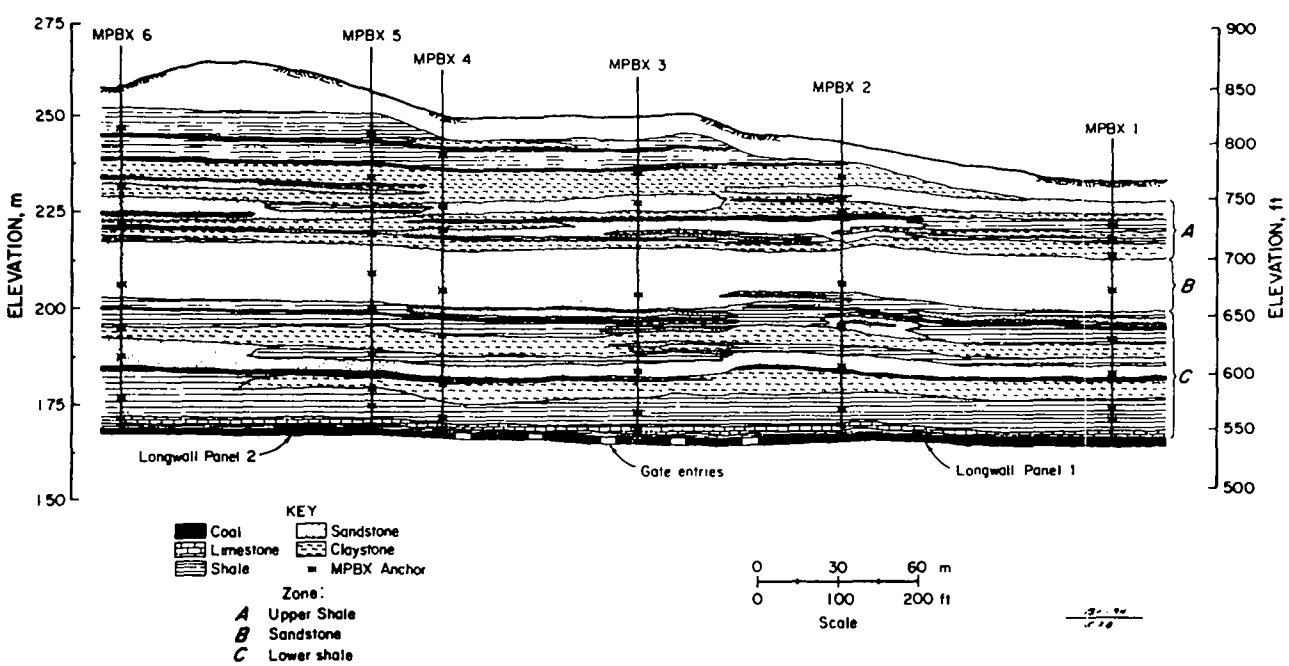


Figure 3. Generalized cross section of study area and MPBX locations

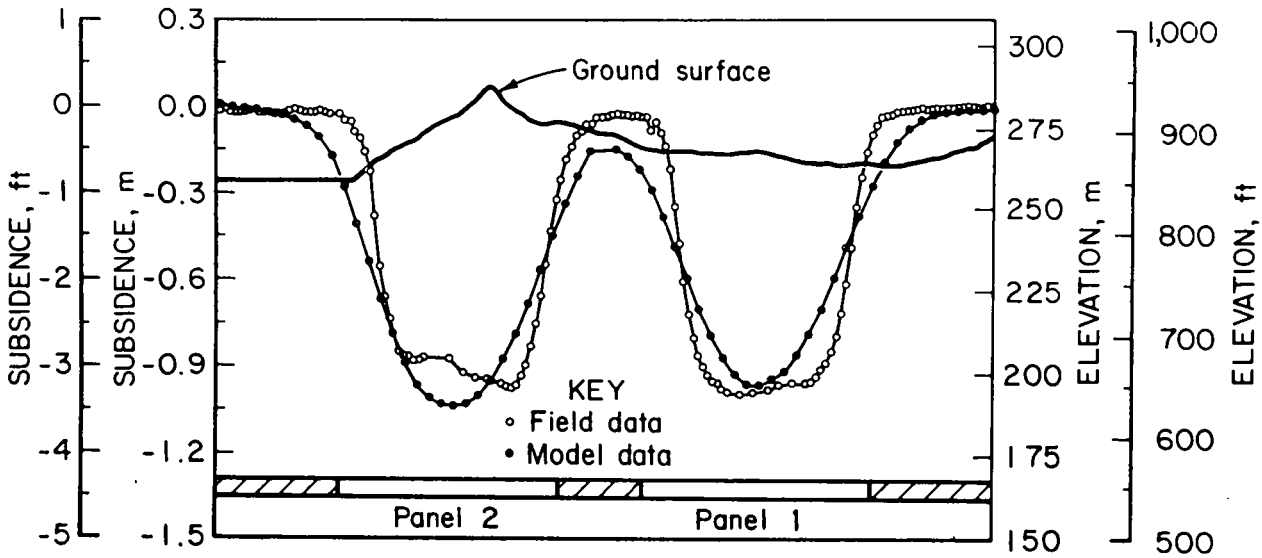


Figure 4. Comparison of field data and model subsidence profiles

Table 1.—Input parameters for generation of subsidence profile

Input Parameter	Overburden Material	Coal Layer
E, MPa (psi)	1,550 (2.2 x 10^5)	1.56 (2.2 x 104)
n	0.30	0.30
D, kg/m³ (lb/ft³) . .	2,400 (150)	390 (80)
E_{insitu}/E_{failed}	4.0	4.0
$n_{post\ failure}$	0.450	0.450

E = Modulus of Elasticity.
D = Density.
n = Poisson's ratio.

The values of the modulus of elasticity for the overburden were based on lab results obtained from core samples collected from the field site. To obtain the model inputs, an average of all field samples was calculated (3.0 x 10^9 kg/m² (6.4 x 10^8 lb/ft²)) and ratios of 1/20 for the overburden material and 1/200 for the coal material were applied to the average lab result. Prior research has shown that decreasing E_{lab} values by several orders of magnitude, results in a better representation of actual field conditions and accounts for rock mass effects (Voight 1970). Voight (1970), has also noted that lab results within the range of 4.88 x 10^6 to 4.88 x 10^8 kg/m² (1.0 x 10^6 and 1.0 x 10^8 psi) should be reduced by at least one order of magnitude. A value of 4.0 was inputted into the model for the postfailure ratio of $E_{in\ situ}/E_{failed}$. This ratio is simply a curve fitting parameter to match the field-measured maximum subsidence magnitude with that

derived from the model. In reality, the form of the subsidence profile predicted by the model is insensitive to the choice of elastic parameters. The excavation of coal is simulated using a bimodulus model. Initially, this material is assigned a very small modulus and a Poisson Ratio equal to zero, allowing the material to freely deform in the vertical direction. As the top and bottom of the panel contact each other, the modulus of elasticity value is increased to prevent interpenetration.

Figure 4 shows the subsidence profile determined by the model and the actual subsidence profile obtained from the collected field data. Although the two curves are not identical, the general trends of the curves are similar, with the maximum subsidence located above the two panels. This match is considered adequate for the subsequent hydrologic analyses.

Comparison of Vertical Displacements Determined by the Model and Field Data

Strain distributions are determined in the finite element model by solving the boundary value problem with appropriate constitutive relations. The subsidence profile is the surface manifestation of this continuous redistribution of strain surrounding the mined panel. Strains and displacements generated within the mesh, as a result of mining, may also be determined and analyzed. A comparison of vertical displacements, within the overburden, as generated by the model and the displacements measured at the field site are shown in tables 2-4.

Table 2.—V_{field} versus V_{model} (vertical displacements) for MPBX nos. 1 and 2

Borehole	Anchor	Height		V_{field}		V_{model}	
		m	ft	m	ft	m	ft
1	1	54.56	179	1.14	3.73	1.00	3.28
	2	50.60	166	1.16	3.79	1.01	3.30
	3	47.00	154	1.17	3.85	1.01	3.30
	4	38.10	125	1.30	4.26	1.01	3.30
	5	25.91	85	1.50	4.90	1.01	3.30
	6	16.15	53	F	F	1.00	3.28
	7	8.53	28	F	F	1.00	3.25
	8	6.10	20	F	F	1.00	3.25
2	1	64.62	212	0.57	1.87	0.50	1.63
	2	57.91	190	0.57	1.87	0.50	1.63
	3	55.17	181	0.60	1.98	0.50	1.63
	4	38.71	127	0.70	2.27	0.51	1.68
	5	27.74	91	1.64	5.37	0.51	1.68
	6	18.59	61	F	F	0.52	1.71
	7	9.45	31	F	F	0.53	1.73
	8	5.18	17	F	F	0.53	1.74

F - Anchor Failed
A - Anchor Number

Table 3—V_{field} versus V_{model} (vertical displacements) for MPBX nos. 3 and 4

Borehole	Anchor	Height		V_{field}		V_{model}	
		m	ft	m	ft	m	ft
3 . . .	1	70.10	230	0	0	0.09	0.29
	2	60.35	198	0	0	0.07	0.23
	3	36.90	121	0	0	0.07	0.22
	4	16.70	55	0	0	0.07	0.24
	5	7.01	23	0	0	0.07	0.24
	6	2.44	8	0	0	0.07	0.24
	7	0.91	3	0	0	0.07	0.24
	8	0.30	1	0	0	0.07	0.24
4 . . .	1	70.71	232	0	0	0.30	0.99
	2	58.52	192	0	0	0..27	0.88
	3	52.73	173	0	0	0.25	0.82
	4	36.88	121	0	0	0.21	0.70
	5	25.30	83	0	0	0.19	0.62
	6	13.41	44	0	0	0.16	0.52
	7	3.96	13	0	0	0.14	0.47
	8	1.83	6	0	0	0.12	0.41

F - Anchor Failed
A - Anchor Number

Table 4 —V_{field} versus V_{model} (vertical displacements) for MPBX nos. 5 and 6

Borehole	Anchor	Height		V_{field}		V_{model}	
		m	ft	m	ft	m	ft
5 . . .	1	83.21	273	1.21	3.97	0.56	1.85
	2	64.00	210	1.28	4.20	0.56	1.85
	3	50.30	165	1.43	4.70	0.56	1.84
	4	39.62	130	1.44	4.73	0.56	1.85
	5	31.10	102	1.53	5.01	0.56	1.85
	6	19.2	63	F	F	0.59	1.93
	7	10.36	34	F	F	0.60	1.96
	8	5.80	19	F	F	0.61	1.99
6 . . .	1	75.60	248	1.09	3.56	1.10	3.62
	2	62.79	206	F	F	1.11	3.63
	3	51.21	168	1.10	3.62	1.12	3.66
	4	38.10	125	F	F	1.12	3.66
	5	27.43	90	F	F	1.11	3.64
	6	19.50	64	1.14	3.73	1.11	3.61
	7	9.45	31	F	F	1.09	3.57
	8	3.96	13	F	F	1.08	3.53

F - Anchor Failed
A - Anchor Number

The predicted vertical displacement data obtained from the model for MPBXs Nos. 1, 2, 3, and 6 correlate well with the field data collected at the site (tables 2-4). The field displacement data for MPBX No. 4 (table 3) showed minimal vertical displacement, whereas, the predicted vertical displacements for these boreholes showed slightly higher magnitudes of displacement (.07 to .30 m) (0.22 to 0.99 ft). One contributing factor could be the difference between the predicted subsidence profile and the actual field data (figure 4). As displayed in the figure, the field data profile shows minimal amounts of subsidence occurring above the gate roads between the two panels. Whereas, the predicted subsidence profile shows a maximum of 0.15 m (0.5 ft) subsidence.

The anchors in MPBX No. 5 displayed larger magnitudes of vertical displacements as compared to those predicted by the model. Again, this is mainly attributed to the differing shapes of the subsidence profiles above the vicinity of the ribline over panel No. 2 (figure 4). The profile, developed from the model, shows less subsidence occurring above the ribline as compared to the profile determined from the field data. As shown in the figure, the maximum subsidence (field data) for panel No. 2 occurs near the ribline, whereas, the model predicted maximum subsidence to occur above the center of the panel. This nonclassical form of the subsidence profile is attributed to site-specific geological conditions that are undefined and therefore not incorporated into the homogeneously distributed material parameters used in the finite element evaluation of displacements.

Correlation of the Postmining Hydrologic Regime with Data Collected from Field Site

The postmining effects to the ground water system (figure 5), evaluated from the model, were determined though input of the parameters as shown in table 5.

Table 5.—Input parameters for determination of postmining ground water effects

Input Parameter	Overburden Upper Shale	Overburden Sandstone	Overburden Lower Shale
K_x, Horizontal Conductivity	7.01×10^{-8} m/s (2.3×10^{-7} ft/s)	7.01×10^{-5} m/s (2.3×10^{-4} ft/s)	7.01×10^{-9} m/s (2.3×10^{-8} ft/s)
K_y, Vertical Conductivity	7.01×10^{-8} m/s (2.3×10^{-7} ft/s)	7.01×10^{-5} m/s (2.3×10^{-4} ft/s)	7.01×10^{-9} m/s (2.3×10^{-8} ft/s)
S, Fracture Spacing	0.31 m (1 ft)	0.91 m (3 ft)	0.10 m (0.30 ft)
R_m, Modulus Reduction Factor	0.80	0.05	0.97
ν, Kinematic Viscosity	1.0×10^{-6} m²/s (1.0×10^{-5} ft²/s)	1.0×10^{-6} m²/s (1.0×10^{-5} ft²/s)	1.0×10^{-6} m²/s (1.0×10^{-5} ft²/s)
g, Acceleration of Gravity	9.81 m/s² (32.2 ft/s²)	9.81 m/s² (32.2 ft/s²)	9.81 m/s² (32.2 ft/s²)
I, Infiltration Rate	0.23 m/yr (0.75 ft/yr)	0	0

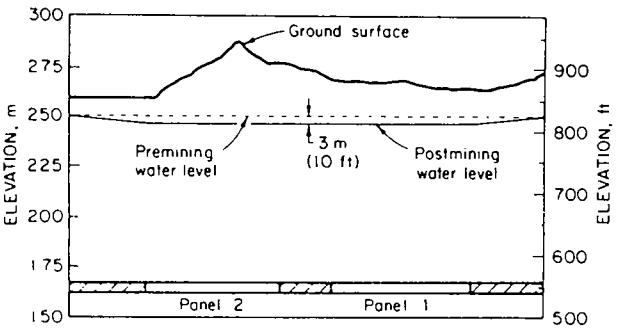


Figure 5. Postmining effects of ground water system - predicted by model. Flow rate - Q = 2,390 Lpm (630 gpm)

Numerous drawdown and recovery pumping tests were performed on all of the monitoring wells to determine hydraulic conductivity values. The hydraulic conductivity value of the 7.01×10^{-8} m/s (2.3×10^{-7} ft/s), upper overburden material (shale), for input to the model, was determined by averaging the hydraulic conductivity values measured at the site. The estimated hydraulic conductivity value, 7.01×10^{-5} m/s (2.3×10^{-4} ft/s) for the sandstone material was used as input into the model. This value was 3 orders of magnitude greater than the measured conductivity value obtained for the upper overburden material. This value of hydraulic conductivity was used because it is believed that the sandstone unit provides a much higher permeability than that of a shale unit. The hydraulic conductivity for the lower overburden material (shale) was one order of magnitude less than that of the upper material 7.01×10^{-9} m/s (2.3×10^{-8} ft/s). Prior USBM research has shown that fractures within the overburden rock mass commonly decrease in aperture and number with increasing depth (Walker 1986). Correspondingly, the rock mass at depth is assumed 'tighter' and consequently less conductive.

The fracture spacing values used are assumed, since no information regarding fracture spacings were determined at the field site. However, the selected values are consistent with those incorporated in other successful calibration studies (Elsworth 1994, Liu 1994, and Ouyang 1993). As mentioned earlier, the modulus reduction factor, R_m, reflects the partitioning of mining-induced strains between fractures and the porous matrix. In less stiff materials, the matrix accommodates proportionately more of the applied bulk strain than stiffer materials, where fracture closure dominates the mass response. Correspondingly, less competent materials, such as shales, return higher magnitudes of the modulus reduction factor. In the absence of field measured magnitudes, appropriate magnitudes of the modulus reduction factor are selected, reflecting these anticipated characteristics of behavior.

Flow rates entering the mine following the excavation of both panels were monitored by the mining company. Mine personnel estimated flow rates through the monitoring of a main sump located underground. Effects of surface area, lithology, and hydrogeology were incorporated into the analysis to determine flow rate estimates. This information provided a reasonable basis for the selection of several values for input into the model i.e., fracture spacing (s) and modulus reduction factor (R_m). The flow rate provided by the mining company was approximately 2,390 lpm (630 gpm). Values of R_m, determined through matching the flow rate, were 0.80 for material 1, 0.05 for material 2, and 0.97 for material 3. Choice of these parameters was clearly non-unique, but was predicted on the anticipated response of the lithologic units to straining and fracturing. The pre-existing fractures in the upper shale and the lower shale units have less effects on the postmining conductivities than those in the

sandstone layer unit. Actually, the shale material may be treated as a porous medium which is not sensitive to deformation. The difference between the two values is due to the effect of depth. The value of R_m is chosen as 0.05 for the sandstone unit because a large part of the extensional strain is applied to the fracture system and precipitates the largest possible change in conductivity.

The coarse finite element mesh, used to evaluate the subsidence profile and overburden displacements, was applied to determine the influence of mining-induced permeability changes on the ground water system. The predicted effects on the postmining ground water system determined by the model correlated well with the field data collected at the site as shown in figures 6-11. Figures 6-11 show water level fluctuations measured for Well Nos. 1-6, respectively. In addition, curves were added to the figures which show progression of the longwall face as a function of the overburden thickness. These values are expressed as the ratio of face position (FP) to overburden thickness (OB). For example, consider a longwall face that is moving towards a well but is 183 m (600 ft) away and the overburden at the site of the well is 61 m (200 ft). The FP/OB ratio is - 3. The negative value of FP/OB ratio indicates a premining position of the longwall face; zero indicates when the respective longwall face passed beneath the line of wells; and a positive value indicates postmining positions of the longwall face past the line of wells. If at another site a longwall face was approaching a well but was 366 m (1,200 ft) away and the thickness of the overburden at the site of the well was 122 m (400 ft), the FP/OB ratio is still -3. This curve allows one to compare well response at two different sites (conceivably in the same study area) without having too make complicated adjustments for differing overburden thicknesses. Under the applied boundary conditions, the model determined that a static decrease of 3.0 m (10 ft) in water level would occur due to the mining of both longwall panels. It should also be noted, that this decrease would occur without an infiltration rate inputted in the model. If an infiltration rate of 0.23 m/yr (0.75 ft/yr) is used, the regional model predicts that essentially no effects to the static phreatic surface would result. This infiltration rate is 25% of the total precipitation occurring at the site and correlates well with known infiltration rates of previous studies (Stoner 1983). Precipitation records provided by the mining company showed an average precipitation of 0.91 m (3.0 ft) which occurred at the site. Therefore, an infiltration rate of 0.23 m/yr (0.75 ft/yr) was used. Figure 5 shows the model prediction after excavation of both longwall panels.

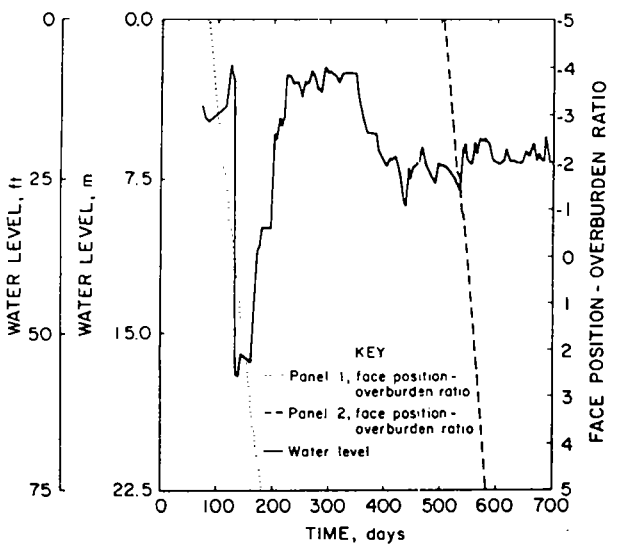


Figure 6. Comparison of water level change and face position to overburden ratio for Well 1

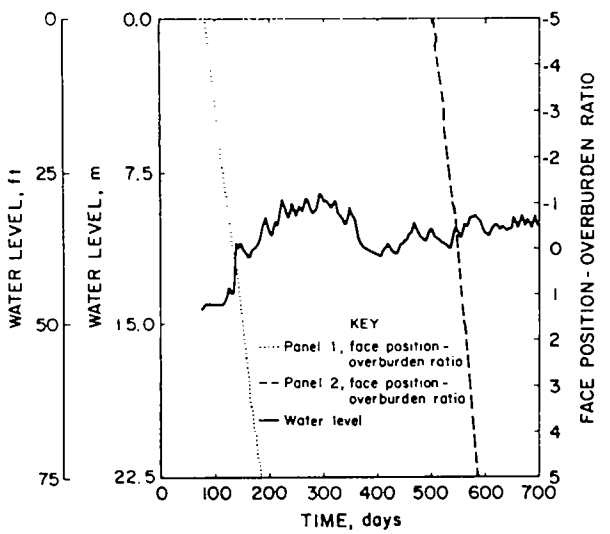


Figure 7. Comparison of water level change and face position to overburden ratio for Well 2

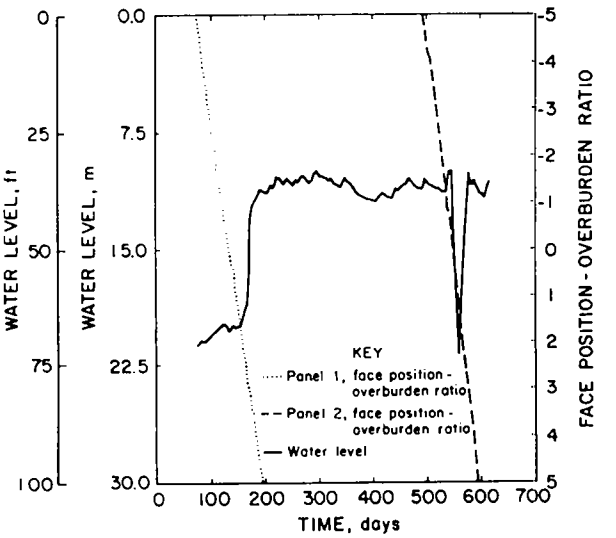


Figure 9. Comparison of water level change and face position to overburden ratio for Well 4

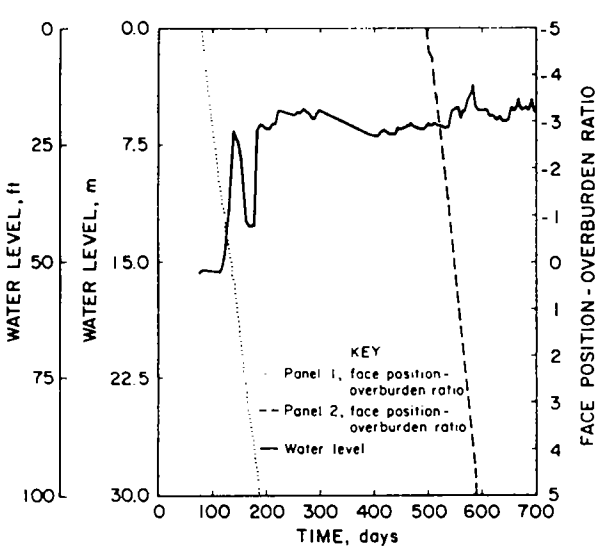


Figure 8. Comparison of water level change and face position to overburden ratio for Well 3

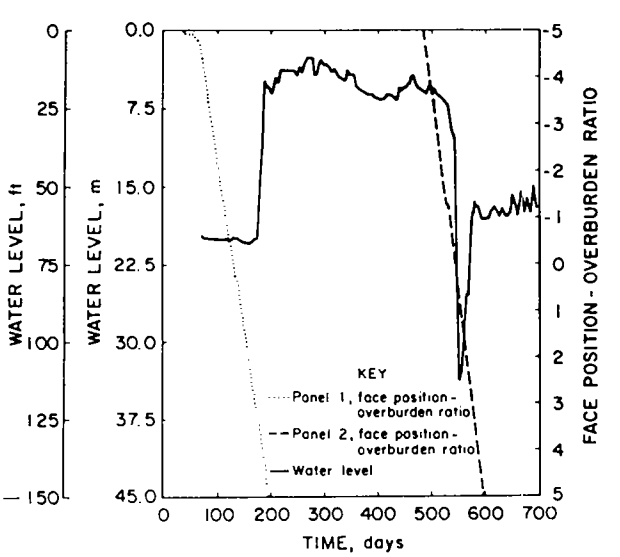


Figure 10. Comparison of water level change and face position to overburden ratio for Well 5

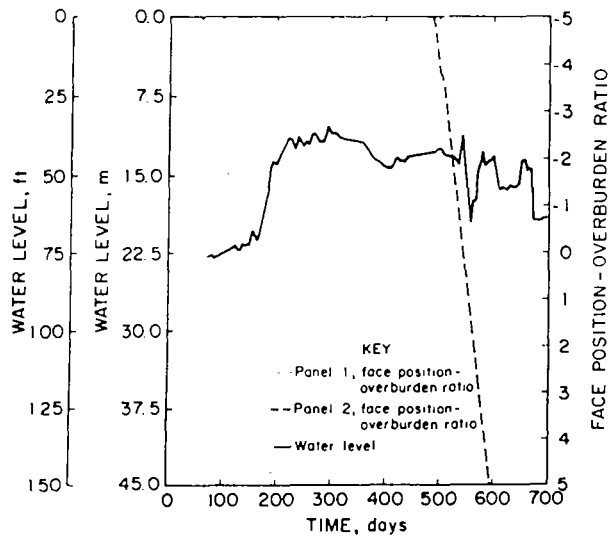


Figure 11. Comparison of water level change and face position to overburden ratio for Well 6

In addition to applying the regional model, described above, local behavior around the shallow well field (figure 12a) was also represented by a more refined model to accommodate more subtle water budget changes as a result of mining. The changes in hydraulic conductivities predicted from the initial calculations were applied to the zonation as defined in figure 12*b*. These zones represent average changes in hydraulic conductivities evaluated from the subsidence modeling. The refined mesh is capable of accurately representing local changes in the location of the phreatic surface. This mesh represents the region between the centerlines of both panels containing well nos. 5 and 6 within Zone I, well nos. 2-4 within Zone II, and well no. 1 within Zone III. No flow boundary conditions were specified along the base and on the left side (the centerline of panel No. 2) and constant head conditions were applied on the remaining vertical side (about 76.2 m (250 ft) away from the centerline of panel No. 1). The mesh, utilized uniform spacing, and was constructed of 326 nodes and 295 elements. Two different situations were simulated through use of the refined mesh. Fist, the same infiltration rate and premining ground water conditions were inputted, where the small-scale influences of topographically induced flow were accommodated. Secondly, the postmining hydraulic conductivity magnitudes of table 5 were incorporated to determine the anticipated postmining ground water levels. The magnitude of hydraulic conductivities were evaluated directly from the spatial distribution of strains, using equations 6 and 7. Average magnitudes of horizontal and vertical conductivities were then utilized in the refined model of figure 12. The changes in hydraulic conductivities are documented in table 6.

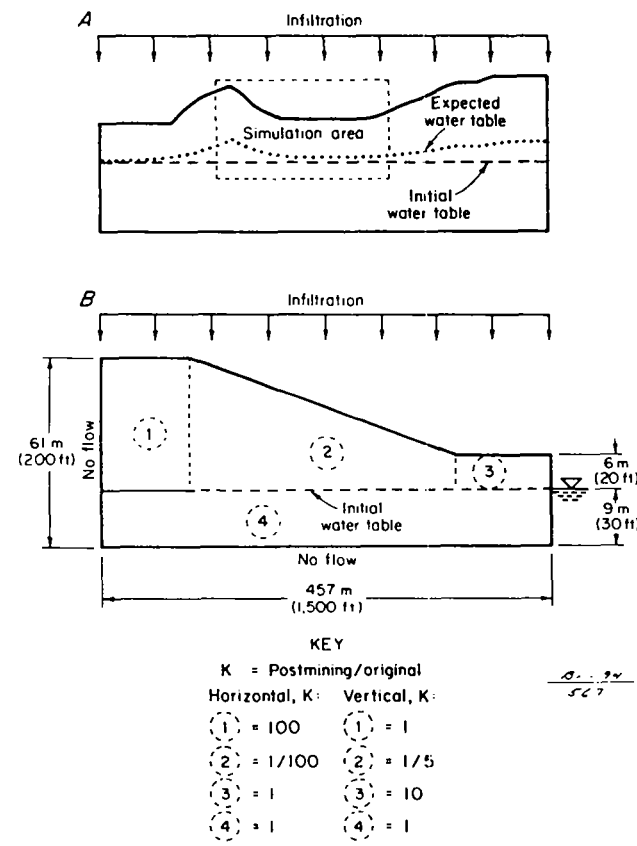


Figure 12. Model for topographic influence of infiltration on well elevations. A, comceptual; B, numerical

Table 6. Relative changes in hydraulic conductivity ($K_{postmining}/K_{original}$) as applied to the small-scale mesh

Zone	K_h	K_v
1	100	1
2	1/100	1/5
3	1	10
4	1	1

K_h = Horizontal conductivity.
K_v = Vertical conductivity.

The resulting postmining modification in the location of the phreatic surface is illustrated in figure 13. The subtle changes result from applying the same infiltration rate as used in the previous model run, however, the greater element density of this revised model highlights the influence of even minor topography and moderate changes in near surface hydraulic conductivities on the ground water system. The mining-induced development of hydraulic conductivities is such that water levels in the region of wells 5 and 6 remain the same, water levels in the region of wells 3 and 4 rise, and water levels in the region of wells 1 and 2 fall, relative to premining water levels. When the long-term recorded levels in these six wells are corrected relative to the control well (a well located approximately 425 m (1,400 ft) away from mining activity), this distribution of behavior, and of this magnitude is exactly as observed from the field measurements performed at the site (Matetic 1991) and as shown in figures 6-11.

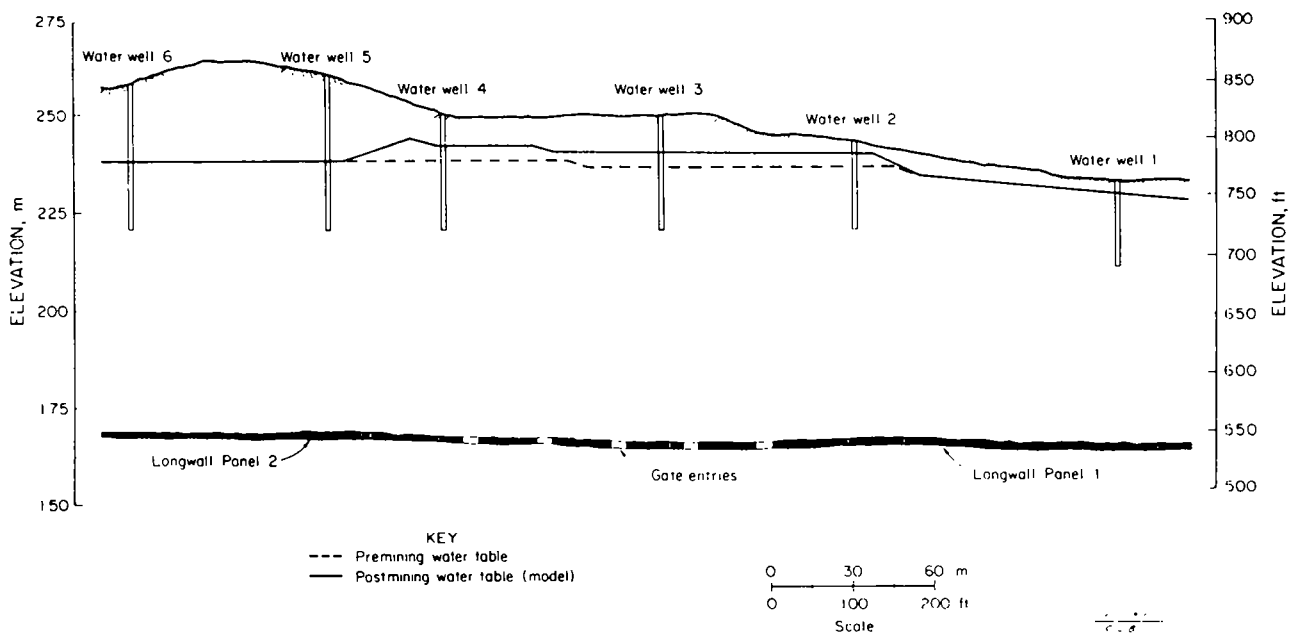


Figure 13. Postmining effects on ground water system using smaller-scale mesh around well area

Summary

1. The subsidence profile, as determined from the model, compares favorably with maximum subsidence measured at the field site.

2. The field data showed that minimal subsidence occurred above the gate roads between the two panels, while the predicted subsidence profile showed a maximum of 0.15 m (0.5 ft) subsidence at this location.

3. The predicted vertical displacement data obtained from the model for MPBX's Nos. 1, 2, 3, and 6 correlated well with the field data.

4. The field displacement data for MPBX No. 4 displayed minimal displacements, whereas, the predicted displacements for these boreholes showed slightly higher displacement. Also, MPBX No. 5 showed similar vertical displacements as compared to that predicted by the model.

5. The predicted effects of the postmining ground water system determined by the model correlated well with the field data collected at the site. Without infiltration added, the model determined that a static decrease of 3.0 m (10 ft) in water level would occur at the site due to the mining of both longwall panel nos. 1 and 2. If an infiltration rate was input to the model, no predicted effects for the long term would occur to the ground water regime which correlates well with field observations.

6. Where a fine mesh is used to define local changes in water budget within the well field area, the model is capable of replicating relatively subtle changes in long-term water levels. Minor local changes in the phreatic surface are consistent with the rolling topography of the site and the effects of mining-induced changes in hydraulic conductivity.

Conclusion

For this study, the numerical modeling results correlate favorably with the field data collected at the site. The surface subsidence information from the field, provided an excellent foundation for the modeling routine. If this information is not available, one should obtain and examine available subsidence prediction models to determine the profile information for the site. The assumptions made during the course of operating the model were based on knowledge of the subject area, experience with the model and insight gained from field tests. Again, if the field information is not available, the model routine requires some additional assumptions. Although a favorable correlation exists between the mining effects predicted and the field data collected, the authors feel that additional comparative studies at research sites with varying geology, longwall panel characteristics (thickness, width, etc.), hydrogeology, etc. should be performed to further substantiate the capabilities of the model.

References

Booth, C. J. Hydrogeologic Impacts of Underground (Longwall) Mining in the Illinois Basin. Paper in Procs. of the 3rd Workshop on Surface Subsidence Due to Underground Mining, Morgantown, WV, June 1-4, 1992, WVU, 1992, pp. 222-227.

Elsworth, D., Liu, J. and Z. Ouyang. Some Approaches to Determine the Potential Influence of Longwall Mining on Ground Water Resources. Paper in Procs. of the International Land Reclamation and Mine Drainage Conference and Third International Conf. on the Abatement of Acidic Drainage, Pittsburgh, PA, April 24-29, 1994), Vol 4 of 4, NTIS, 1994, pp. 172-179.

Johnson, K. L. Influence of Topography on the Effects of Longwall Mining on Shallow Aquifers in the Appalachian Coalfield. Paper in Procs. of the 3rd Workshop on Surface Subsidence Due to Underground Mining, Morgantown, WV, June 1-4, 1992, WVU, 1992, pp. 197-203.

Leavitt, B. R. and J. F. Gibbens. Effects of Longwall Coal Mining on Rural Water Supplies and Stress Relief Fracture Flow Systems. Paper in Procs. of the 3rd Workshop on Surface Subsidence Due to Underground Mining, Morgantown, WV, June 1-4, 1992,. WVU, 1992, pp. 228-235.

Liu, J. Topographic Influence of Longwall Mining on Water Supplies. M.S. Thesis, The Pennsylvania State University, University Park, PA, 1994, 73 pp.

Matetic, R. J., M. A. Trevits, and T. Swinehart. A Case Study of Longwall Mining and Near-Surface Hydrological Response. Paper in Procs. of the 1991 American Mining Congress Coal Convention, Pittsburgh, PA, June 2-5, 1991, AMC, 1991, pp. 445-472.

Matetic, R. J. and M. A. Trevits. Longwall Mining and its Effect on Ground Water Quantity and Quality at a Mine Site in the Northern Appalachian Coalfield. Paper in Procs. of the FOCUS Conference on Eastern Regional Ground Water Issues, Newton, MA, October 13-15, 1992, Water Well Journal Publishing Company, 1992, pp. 573-587.

Matetic, R. J. and M. A. Trevits. Case Study of Longwall Mining Effects on Water Wells. Paper in Procs. of the SME Annual Meeting, Salt Lake City, UT, Feb. 26-Mar. 1, 1990, SME preprint 90-141, 1990, 7 pp.

Ouyang, Z. and D. Elsworth. Evaluation of Groundwater Flow into Mined Panels. International Journal of Rock Mechanics, Mineral Sciences and Geomechanics, V. 30, No. 2, 1993, pp 71-79.

Stoner, J. D. Probable Hydrologic Effects of Subsurface Mining. Ground Water Monitoring Rev., Winter 1983, pp. 128-138.

Tieman, G. E. and H. W. Rauch. Study of Dewatering Effects at a Longwall Mine in Northern West Virginia. Paper in Procs. of the 3rd Workshop on Surface Subsidence Due to Underground Mining, Morgantown, WV, June 1-4, 1992, WVU, 1992, pp. 214-221.

Trevits, M. A. and R. J. Matetic. A Study of the Relationship Between Saturated Zone Response and Longwall Mining-Induced Ground Strain. Paper in Procs. of the 5th Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, Las Vegas, NV, May 13-16, 1991, Water Well Journal Publishing Company, 1991, pp. 1101-1109.

Voight, B. and W. Pariseau. State of Predictive Art in Subsidence Engineering. Journal of Soil Mechanics and Foundations Division, V. 96, No. SM 2, 1970, pp. 721-750.

Walker, J. S., J. B. Green, and M. A. Trevits. A Case Study of Water Level Fluctuations Over a Series of Longwall Panels in the Northern Appalachian Coal Region. Paper in Procs. of the 2nd Workshop on Surface Subsidence Due to Underground Mining, Morgantown, WV, June 9-11, 1986, WVU, 1986, pp. 264-269.

GROUNDWATER CONDITIONS AROUND A COAL-COMBUSTION RESIDUE SITE IN SOUTHERN ILLINOIS

by

Steven Esling, Merryn Fielding and Bradley Paul

Abstract. Coal-combustion residues, predominantly composed of scrubber sludge, served as backfill to an abandoned surface-mine pit. A low-relief valley now trends across the area that was once the old pit, replacing the former hummocky terrain left by the mining operations. Twelve wells, installed within and adjacent to the fill, provide data on hydraulic head at the base of the spoil, in the coal, and in the coal-combustion residues. The bases of the screens ranged in depth from 5.6 to 15.9 m. Three of the wells were sampled for groundwater chemistry. Hydraulic conductivity of the spoil from nine falling-head (slug) tests ranged from $1.9X10^{-7}$ to $4.1X10^{-3}$ cm/s, with a geometric mean of $1.8X10^{-4}$, somewhat greater than the $9.8X10^{-6}$ cm/s hydraulic conductivity of the coal-combustion residues. The mine spoil is heterogeneous, composed of disturbed surficial sediment, including loess and diamicton, blended with fragments of bedrock. Prior to reclamation, groundwater flowed away from the pit lake to topographic lows to the north, east, and south. Reclamation has not altered groundwater flow significantly. A two-dimensional numeric random-walk contaminant-transport model, based on 1) properties of the coal-combustion residue as determined from column studies, 2) data from a finite difference model of groundwater flow at the site, and 3) conservative estimates of dispersivity and porosity, suggests that leachate generated by the fill poses little threat to ambient groundwater quality.

Additional Key Words: Groundwater Modeling, Groundwater Quality, Mine Land Reclamation

Introduction

In an effort to meet new federal emission standards, power companies rely on scrubbers or employ new coal burning technologies, both of which lead to increased production of coal-combustion residues. Although these materials have numerous applications, including structural fill, light-weight aggregate, stabilization material, drilling fluid, and additive to Portland cement, production will exceed demand for the foreseeable future. Today, most excess residue produced from coal-combustion is either buried near the surface in a relatively dry state (landfill) or pumped into slurry ponds (Bahor and others, 1981), both of which take land suited for other purposes out of production, at least temporarily. Reclaiming abandoned strip-mines with these residues reduces the loss of productive land and returns otherwise non-productive and hazardous land to more productive use.

Coal-combustion residues, however, may produce a leachate containing hazardous substances. Numerous previous studies have investigated the environmental impact of coal-combustion residue disposal

[1]Paper presented at the 1996 Annual Meeting of the American Society for Surface Mining and Reclamation, Knoxville, Tennessee, May 19-25, 1996. Publication in this proceedings does not prevent authors from publishing their manuscripts, whole or in part, in other publication outlets.

[2]Steven Esling, Associate Professor, Merryn Fielding, Research Assistant, Department of Geology, Bradley Paul, Associate Professor, Department of Mining Engineering, Southern Illinois University, Carbondale, IL 62901

sites on surface water and groundwater quality (Villaume and others, 1983; Le Seur Spencer and Drake, 1987; Cherkauer, 1980; Hardy, 1981; Simsiman and others, 1987; Sakata, 1987; Theis and others, 1978; Beaver and others, 1987; Fruchter and others, 1988; Gerber, 1981; Le Seur, 1985; Hall, 1977; Rai and others, 1989; Rehage and Holcombe, 1990; Libicki, 1978; U.S. Waterways Experiment Station, 1979). Some of this research detected distinct contaminant plumes in the groundwater, downgradient from slurry ponds and landfills. In some cases, contaminants exceeded drinking water standards. Adriano and others (1980), Ferraiolo and others (1990), Theis and Marley (1979), and Theis and Gardner (1990) provided general reviews on residue disposal methods and environmental impacts.

This paper presents intermediate results of a long-term study of the environmental impact of filling an abandoned strip-mine pit in southern Illinois with coal-combustion residues. An unstable highwall associated with the pit threatened a county road. The immediate area lacked sufficient spoil needed to fill the strip-pit and establish a gentle graded contour. Coal-combustion residues, predominantly composed of flue-gas desulferization scrubber sludge with lesser amounts of fly ash, herein referred to as *residues*, served as a backfill.

Site Description

General Setting

The study area is an abandoned strip-mine located within the Herrin 7.5-Minute Topographic Quadrangle, just east of Energy, in Williamson County, Illinois. A private landfill and the Herrin Municipal landfill are located in the section to the north. The test site (figure 1) was an abandoned strip-pit lake that was partially filled with debris from the surrounding spoil piles and an adjacent highwall. The pit, which was about 315 m long, 50 m wide, and up to 12 m deep (as measured from the top of the highwall), was filled in stages. Initial work during the summer of 1993 reclaimed the western 90 m of the pit, with the residues filling the first 70 m of the pit behind a 20-m-wide spoil dam. Reclamation was completed during the summer of 1994, with residues filling the next 90 m and spoil filling the remaining 135 m of the pit. Two other abandoned pits are nearby, one to the west of the disposal site (West Pit) and the other to the south and east (South Pit).

Pre-strip-mining topographic maps clearly show that the test site was located on a drainage divide. Flow from the adjacent drainage basins emptied into the Big Muddy River to the north. At present, no distinct surface drainage flows away from the project site, as surface mining operations have disrupted the original drainage pattern and created a hummocky terrain, characterized by numerous small hills, swales, and depressions. Reclamation associated with the placement of the coal-combustion residues has created a more subdued topography with a gentle slope trending to the east in place of the abandoned pit.

Geologic Setting

The test site is on the southern edge of the Illinois Basin and lies within the outcrop zone of the Carbondale Formation (Pennsylvanian). The Paleozoic strata dip gently to the north toward the center of basin. No major faults exist within a 1.6 km radius of the project site. About 5 km to the west, however, several distinct fault systems cut the Pennsylvanian rocks. The Carbondale Formation is characterized by numerous shale, sandstone, limestone and coal members, many of which are not laterally continuous. Complex depositional environments resulted in abrupt lateral facies changes (Willman and others; 1975).

The undisturbed surficial deposits of the study area originated directly and indirectly from glacial processes. Less than 4 m of Illinoian Age glacial diamicton (Glasford Formation) and 2 m of Wisconsinan Age loess (Peoria and Roxana Silts)

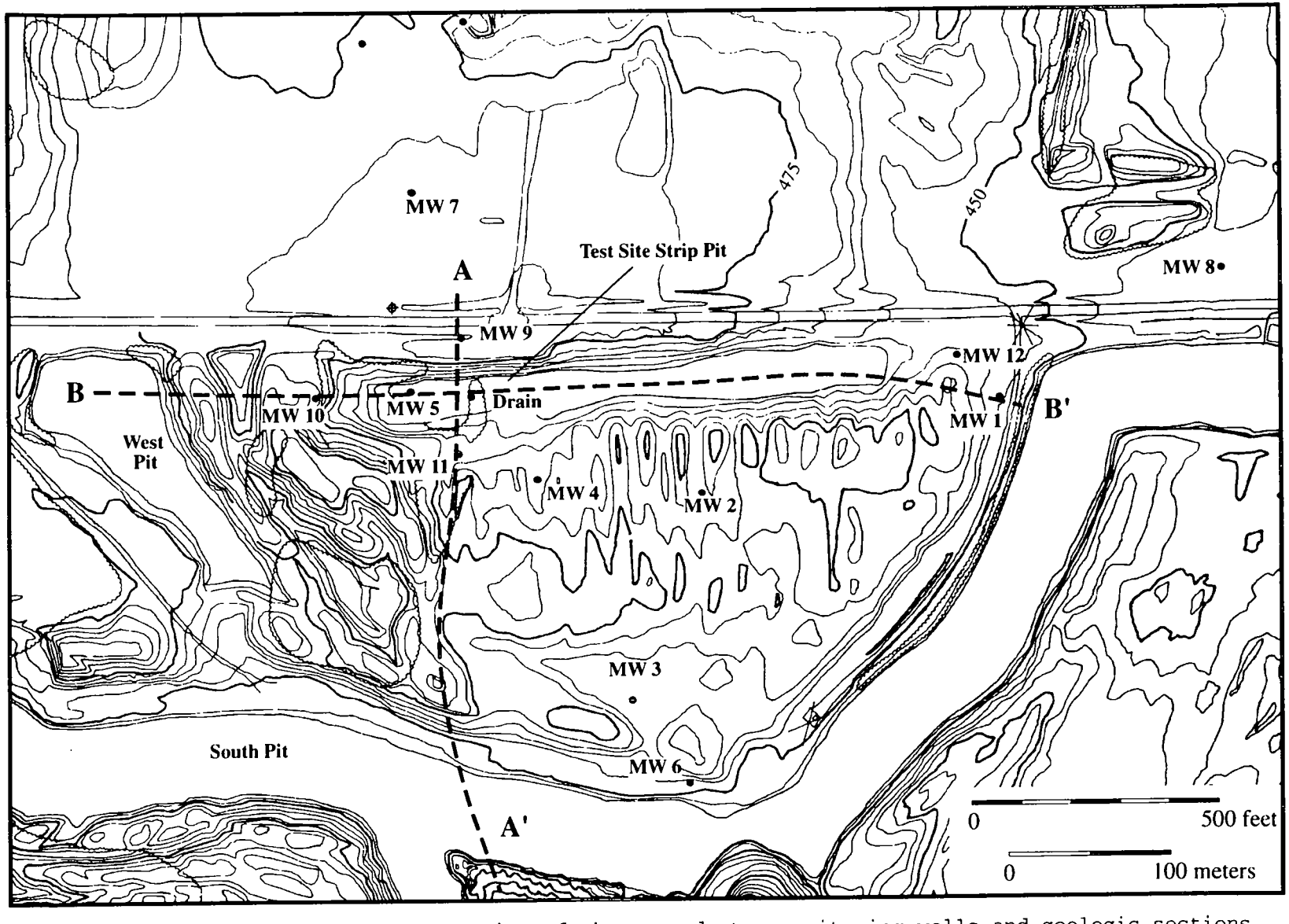


Figure 1. Topographic setting and location of the groundwater monitoring wells and geologic sections. Contour interval is 5 feet.

unconformably overlie the Pennsylvanian strata (Willman and others, 1975).

Strip mining in the study area removed up to six feet of the Herrin Coal seam and all overlying strata, with subsequent replacement of the overburden as spoil. The top of the Herrin Coal is generally at an elevation of about 137 m in the area of the test site. Mine spoil, a mixture of the natural surficial materials and bedrock fragments, constitutes the bulk of the materials on the land surface at the present time. In some places, the spoil consists almost entirely of rock fragments. In other areas, fine-textured matrix materials support the rock fragments.

Two geologic cross-sections (AA', figure 2, and BB', figure 3) constructed from data collected during the installation of monitoring wells, illustrate the general stratigraphy of the study area. Mine spoil lies unconformably on top of strata which underlie the Herrin Coal. Strip-mining operations apparently never removed the coal from beneath the road, but excavation of the highwall proceeded up to its edge.

The Herrin Coal remains in only a few places near the test site. Mining in these areas was either not economic or would have destroyed roads or town structures. Abandoned underground mines also exist near the project site. About 400 m to the north of the test site, the Herrin and Springfield Coals were removed from a room-and-pillar mine, which has since partially collapsed, leaving small subsidence troughs on the surface (Patrick Engineering, 1990).

Hydrologic Setting

Pryor (1956) studied the availability of groundwater in the southern Illinois area, including Williamson county. The report makes no reference to the quality of the water from subsurface supplies and suggests that bedrock units near the test site do not generally yield water, although Pennsylvanian strata elsewhere in the county are capable of sustaining small domestic supplies from depths of 15 to 250 m.

Environmental studies associated with the landfill north of the test site indicate that a shallow unconfined flow system has developed in the spoil and upper, more permeable bedrock units. Reports associated with these projects suggest approximately 3 to 8 m of mine spoil just above the shale unit which presumably underlies the Herrin Coal. Saturated conditions were encountered in all the wells in the unconsolidated materials, suggesting that the shales retard the flow of water moving through the mine spoil. Hydraulic conductivity measured in the field ranged from 10^{-4} to 10^{-6} cm/s, with the higher values in wells screened in coal and black shale (Patrick Engineering, 1990). The hydraulic head data from the monitoring wells suggest groundwater flows to the north at the southern boundary of the landfill and to the south at its northern boundary. The northern and southern flows converge and flow to the east near the center of the landfill (Patrick Engineering, 1990).

Field Investigations

Well Survey

We were unable to locate anyone utilizing a groundwater supply within a 1.6 km radius of the test site. Well logs on file with the Illinois State Geological Survey (ISGS) and Illinois State Water Survey (ISWS) indicate that some water wells were constructed at the turn of the century, but the more recent logs on file were for coal-, gas- or oil- exploration boreholes. A few of the logs of the exploration boreholes suggest brackish (non-potable) groundwater at depths greater than 150 m. Just outside the 1.6 km radius, several water wells were drilled and subsequently abandoned because of poor production.

Monitoring Well Installation

A total of twelve groundwater monitoring wells were installed in the study area for this project (Table 1). Three of the wells were designed to

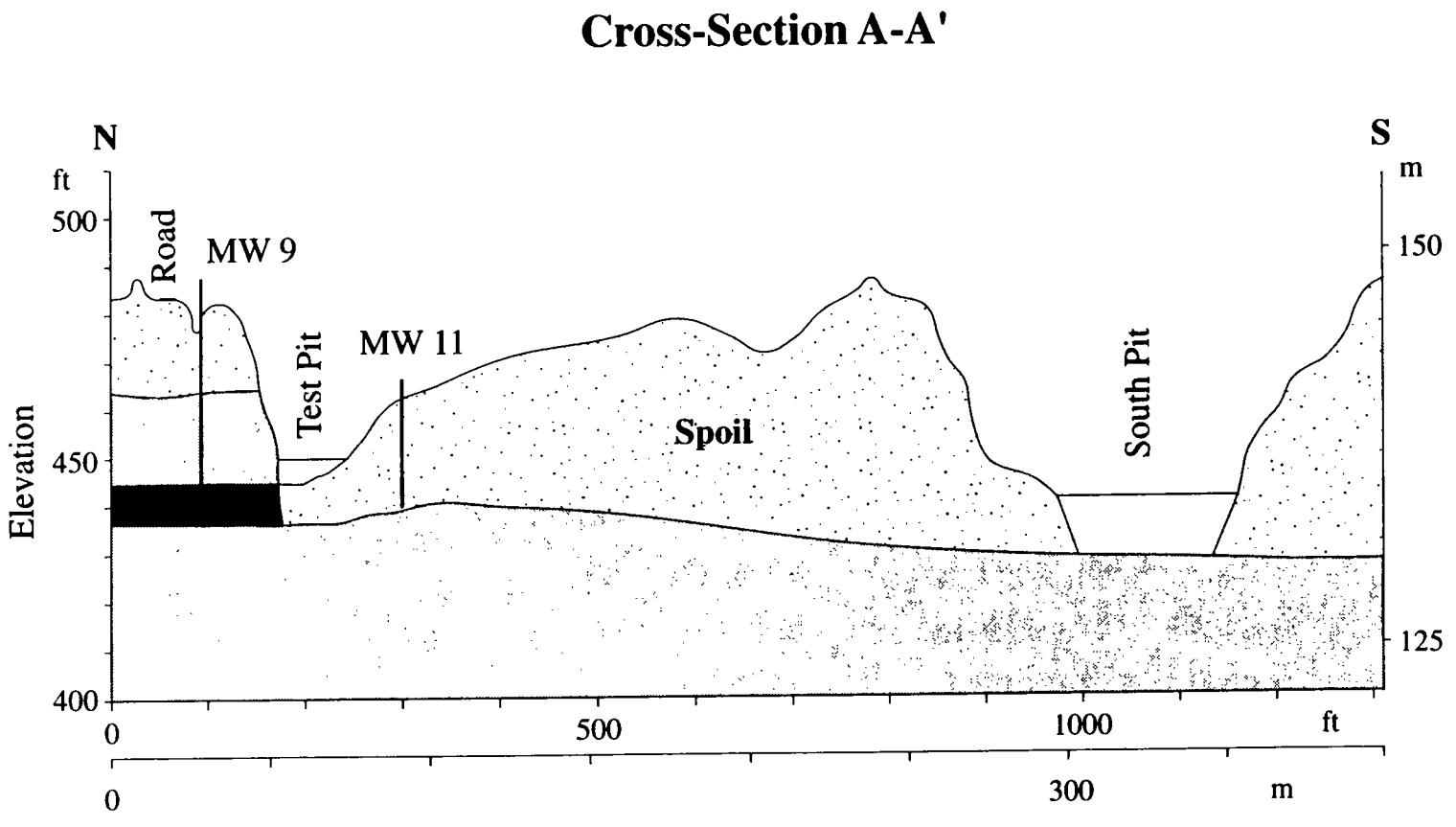


Figure 2. Cross-section showing general stratigraphic relationships along a north-south line through the site. The unit shaded in black is the Herrin Coal. See figure 1 for the location of the section. Verical exaggeration is about 4.95.

Cross-Section B - B'

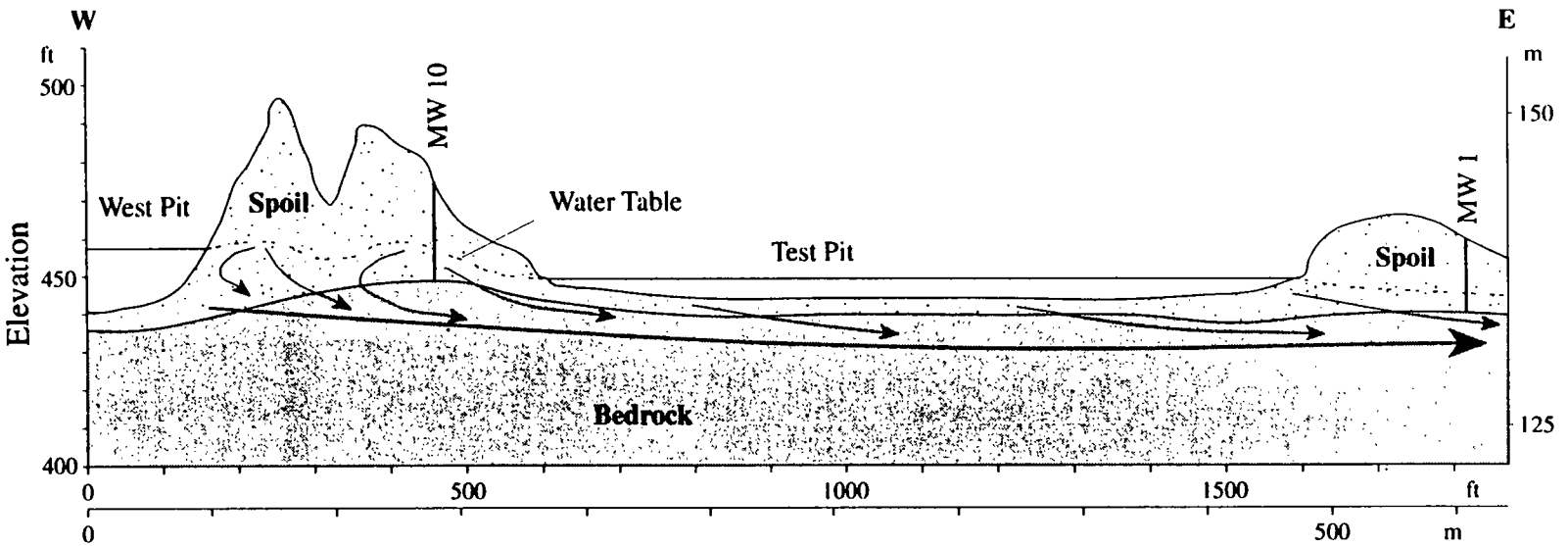


Figure 3. Cross-section showing general stratigraphic relationships and a hypothetical vertical flow system for the study area along a west-east line. See figure 1 for the location of the cross-section. Vertical exageration is about 5.46.

Table 1. Hydraulic conductivity measurements on monitoring wells near the test site.

Monitoring Well	Screened Interval	Maximum Depth (m)	Drilling Method	Hydraulic Conductivity (cm/s)
MW 1	Spoil	5.61	5.25-in Hollow-Stem Auger	$8.4X10^{-5}$
MW 2	Spoil	7.15	5.25-in Hollow-Stem Auger	$4.1X10^{-3}$
MW 3	Spoil	5.63	5.25-in Hollow-Stem Auger	$3.3X10^{-5}$
MW 4	Spoil	5.78	5.25-in Hollow-Stem Auger	$1.8X10^{-3}$
MW 5	Residues	10.32	5.25-in Hollow-Stem Auger	$9.8X10^{-6}$
MW 6	Spoil	5.91	5.25-in Hollow-Stem Auger	$1.9X10^{-7}$
MW 7	Fill/ Shale	10.36	5.25-in Hollow-Stem Auger	
MW 8	Spoil	3.94	5.25-in Hollow-Stem Auger	$8.4X10^{-5}$
MW 9	Coal	12.27	Mud Rotary	$6.8X10^{-5}$
MW 10	Spoil	15.89	Mud Rotary	$5.0X10^{-4}$
MW 11	Spoil	6.25	Backhoe	$1.9X10^{-3}$
MW 12	Spoil	9.24	6-in Hollow-Stem Auger	$5.7X10^{-4}$

sample water quality. These wells, herein referred to as MW 9, MW 10, and MW 11, surround the west end of the fill (figure 1). The installation of MW 9 and MW 10 followed accepted guidelines (USEPA, 1986). Monitoring well MW 11 was installed in a spoil pit excavated with a backhoe. A screen and casing (10.2 cm inside diameter(ID)) was centered in a 25.4 cm ID protective polyvinyl chloride (PVC) pipe prior to backfilling the trench. A successful sand pack around the screen was created by alternately adding a few feet of sand to the annular space between the 25.4 and 10.2 cm pipes, then allowing spoil to collapse around the sand by hydraulically lifting the protective pipe. Filling the remaining annular space continued through the same process, first with bentonite pellets and then with a bentonite cement slurry.

The remaining nine monitoring wells (figure 1) only provide data on

hydraulic head, and installation methods did not always follow USEPA guidelines. Table 1 summarizes the drilling method. Monitoring well casings were 5.1 cm ID PVC screen and casing. The annular space between the casing and borehole walls was filled with sand to a level at least 30 cm above the top of the screen. A cap of bentonite pellets with a minimum thickness of 30 cm was constructed above the sand pack, followed by either a bentonite cement slurry or a mixture of bentonite and well cuttings until a depth of about one meter. The remaining annular space was filled with either cement or concrete. A plastic outer casing protects the monitoring wells at the surface.

Wells were developed by alternately surging the well with a plug and bailing. All well elevations as well as staff gauges in the lakes within the test site and to the west and south were surveyed to a common datum. Two wells installed for monitoring hydrologic conditions in and around the private landfill located immediately north of the test site provide additional data on hydraulic head.

A 15-m-long drain was constructed in the west end of the test site prior to the initial reclamation work. The drain is a slotted pipe surrounded by quartz silica sand, with access through a vertical standpipe installed in the spoil dam. The drain captures leachate from the residues, prior to any natural attenuation, and provides samples from what is in effect a field-scale leachate column test.

Hydraulic Conductivity Measurements

Falling-head tests (slug test) were conducted on most wells to collect data on the hydraulic conductivity of the spoil and bedrock (Table 1). A pressure transducer connected to a datalogger with a cable was placed below the water level. A sealed cylindrical plug constructed of PVC and filled with sand was then dropped into the well, raising water level instantaneously. This method prevents contamination of the well by external sources of water. Data on the hydraulic head in the well was recorded by the datalogger along with the time required for the water level to return to within 80 percent of its pre-test level. Data on head and corresponding time were transferred to a personal computer, processed with a spreadsheet program, and analyzed following the procedures described by Hvorslev (1951) to obtain hydraulic conductivity.

Groundwater Hydrology

Flow

This section describes the conceptual model of the groundwater flow system for the project site, as well as the topographic and geologic factors that influence the flow system. The model of flow conditions is based on geologic data collected during the installation of the monitoring wells, previous geologic studies of the area, and hydraulic head data from the lakes and monitoring wells. Other observations supplemented these data, such as the locations of seeps and the depths to saturated conditions noted while drilling boreholes for monitoring well installation.

Figure 4 is a generalized map of hydraulic head at or just below the water table prior to any reclamation work. The map is based on head data collected on November 20, 1992, from the lakes and the seven monitoring wells that existed at that time. The head contours indicate that the lake to the west and within the test site recharge the shallow groundwater system. The lake to the south may also be a recharge point, but such an interpretation would require additional head data farther to the south. Water quality data also suggest that the lakes recharge the shallow groundwater. Lake-water quality is better than that from the sampled monitoring wells, indicating a significant influx of meteoric water. The quality of the water flowing from the lakes degrades as it reacts with the spoil.

If the lakes are recharge points, then MW 2 shows what at first seems to be an anomalous head, 8.5 cm higher

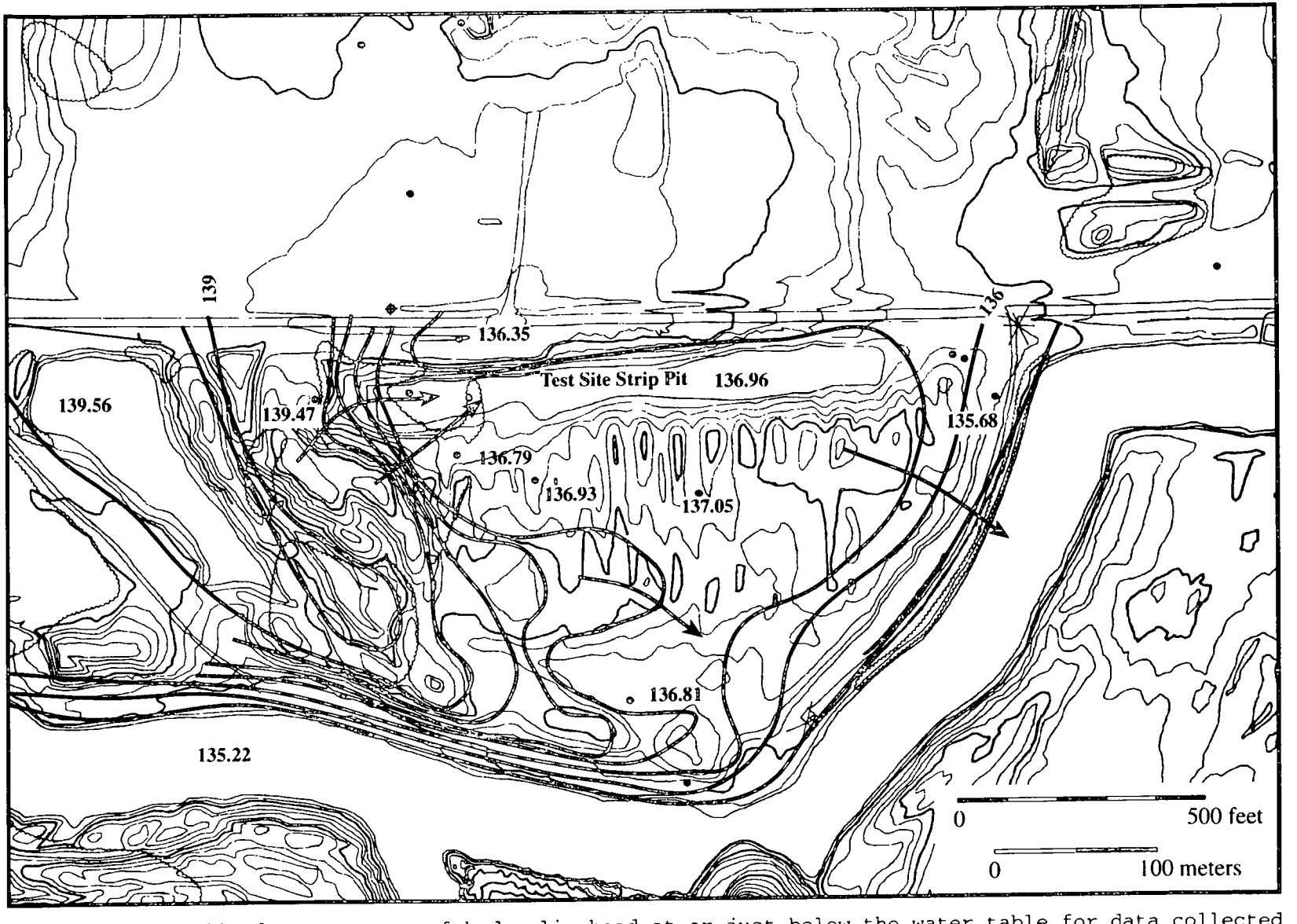


Figure 4. Generalized contour map of hydraulic head at or just below the water table for data collected 11/20/92. Arrows indicate flow direction. Contour interval is 0.6 m.

than the level of the lake water in the test site. Topography, however, influences the general flow pattern at a scale smaller than the map of the groundwater table. If more data were available and the contour interval of head were decreased, smaller local flow systems would become apparent. Typically in a humid temperate climate, like that of southern Illinois, the water table mimics the surface topography. Groundwater recharge occurs over divides, with groundwater discharging into the lows. Observed seeps in the study area suggest this type of system is operating. MW 2 is located near the crest of a spoil pile, and this well is probably influenced by local recharge.

Generally, groundwater flows to the east. Groundwater flows radially away from the lakes and from the center of prominent divides for a short distance before it converges with the general flow system. We need to emphasize that the map is a generalization of a complex flow pattern, ignoring the heterogeneous nature of the spoil. Fractures which can transmit significant quantities of groundwater may be present in the more cohesive spoil. The overall trend, however, does fit the interpretation of flow for the Herrin Landfill located to the northeast (Patrick Engineering, 1990). Flow lines on figure 4 show the shallow flow system at elevations very near the water table. Diagrams like this, however, can cause confusion because they imply horizontal flow when in fact vertical components of flow exist, especially in areas characterized by significant local relief. Figure 3, cross-section BB' (parallel to the interpreted general flow direction from west to east) illustrates the vertical components of flow expected beneath the upland areas.

Why does groundwater flow toward the east? First, mining east of the study area has removed the bedrock units down to the Springfield Coal (Patrick Engineering, 1990). The deep strip-pits and underground mines act as a sink, transmitting significant quantities of groundwater to surface drainage. Second, the study area is located on a topographic high and the elevated water table associated with this high is driving flow toward the east.

Reclamation has altered the original topography in the study area, but the general trends in groundwater flow have not shifted significantly. A map of hydraulic head from data collected in October 1994, after both stages of reclamation, still suggests flow to the east (figure 5).

The maps of hydraulic head were constructed from data collected from monitoring wells screened at the base of the spoil and in the coal. Investigations on the Herrin Landfill (Patrick Engineering, 1990) installed wells into the shallow bedrock. Hydraulic conductivity measurements conducted on these wells suggest that the shallow bedrock and spoil have hydraulic conductivities of similar magnitude in places. If the spoil overlies bedrock units with a lower hydraulic conductivity (such as gray shale), groundwater may concentrate above the bedrock, with flow along the spoil/bedrock interface. If, on the other hand, the spoil overlies rock with comparable hydraulic conductivity, groundwater would flow in the spoil and shallow bedrock, as indicated on figure 3.

The hydraulic conductivity measured in MW 9 is comparable to other values determined in coal (Table 1). Stone and Snoeberger (1977) measured a maximum hydraulic conductivity of 3.1×10^{-4} cm/s for a shallow Wyoming coal. Stoner (1981) reported hydraulic conductivities ranging from 2.3×10^{-4} to 8.1×10^{-5} cm/s for a shallow coal unit in Montana. The hydraulic conductivity determined in the wells with screens in spoil are comparable to those determined for spoil in other environmental studies in the area (Patrick Engineering, 1990). Table 2 summarizes the representative hydraulic conductivities for the various materials encountered in and around the test site.

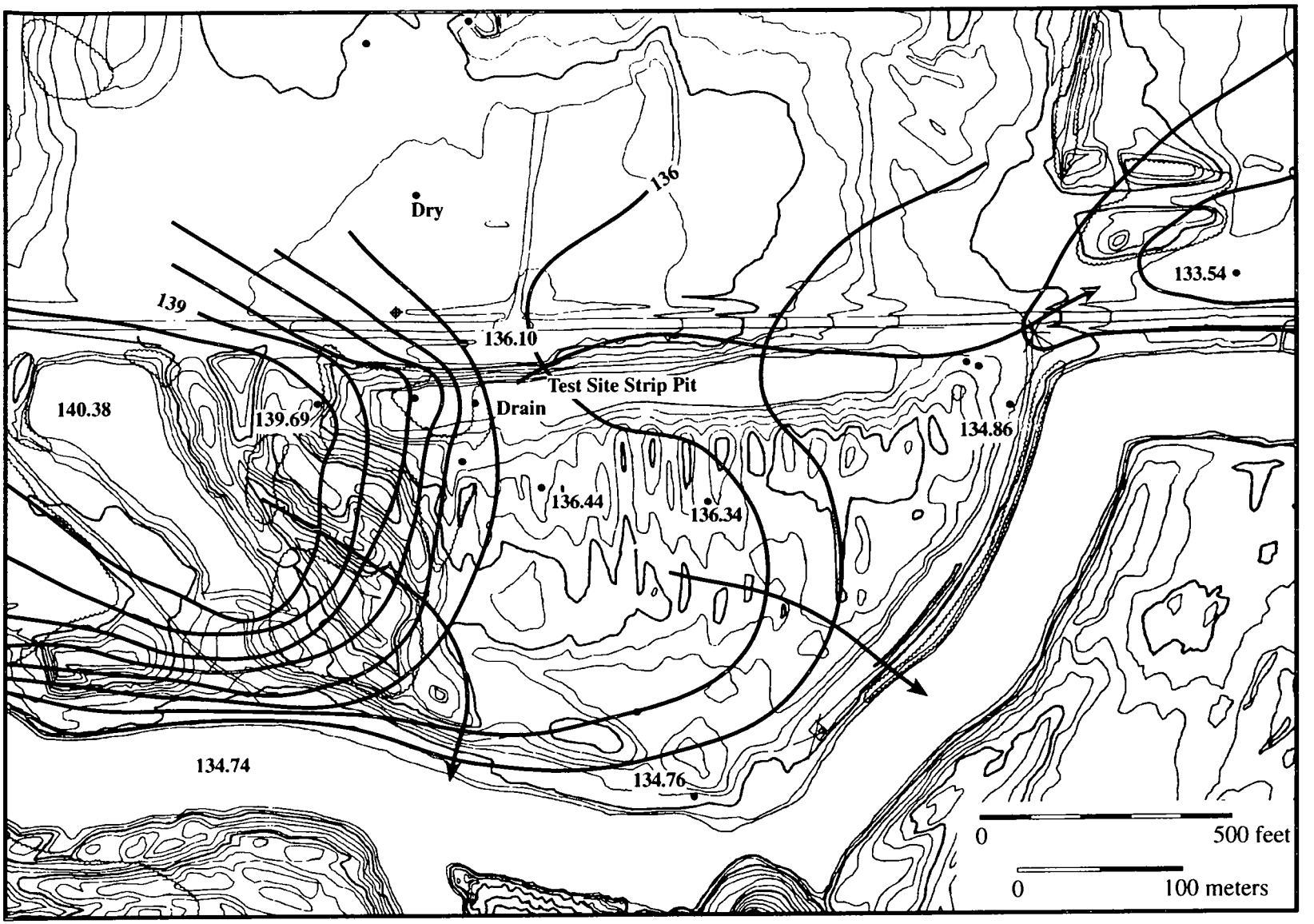


Figure 5. Generalized contour map of hydraulic head at or just below the water table for data collected 10/3/94. Arrows indicate flow direction. Contour interval is 0.6 m.

Fruchter, J.S., D. Rai, J.M. Zachara and R.L. Schmidt 1988. Leachate chemistry at the Montour fly ash test cell. Electric Power Research Institute, EPRI EA-5922, Project 2485-8.

Gerber, Robert G. 1981. Ground water investigations and modeling for a coal ash disposal site in Wiscasset, Maine. Geological Society of America, Abstracts with Programs 13 (3) (Northeastern Section, Bangor, Maine): p. 135.

Hall, D.W. 1977. Hydrogeology of the Saukville fly ash landfill. Unpublished Master's Thesis, University of Wisconsin, Milwaukee.

Hardy, M.A. 1981. Effects of coal fly ash disposal on water quality in and around the Indiana Dunes National Lake Shore, Indiana. U.S. Geological Survey, Water Resources Investigations 81-16, 64 p.

Hvorslev, M.J. 1951. Time lag and soil permeability in groundwater observations. U.S. Army Corps of Engineers Waterways Experimental Station Bulletin 36, Vicksburg, Mississippi.

La Seur, Linda 1985. Hydrogeology of a coal fly ash landfill, Montpelier, Iowa. Unpublished Master's Thesis, University of Iowa, Iowa City, 95 p.

Le Seur Spencer, L. and L. Drake 1987. Hydrogeology of an alkaline fly ash landfill in eastern Iowa. Groundwater 25 (5): 519-526.

Libicki, Jacek 1978. Effects of the disposal of coal waste and ashes in open pits. Final Report, EPA/600/7-78/067, Grant EPA-02-532-10, Industrial Environmental Research Laboratory (Cincinnati, Ohio) 299 p.

Patrick Engineering 1990. Report on the hydrogeological investigation of the Herrin Municipal Landfill. Prepared for the City of Herrin, Patrick Engineering Project Number 395C, Volumes 1 and 2, Patrick Engineering, Glen Ellyn, Illinois.

Paul, B., S. Esling, F. Pisani and K. Krishnamurthy 1992. Reclamation of abandoned strip-mines using coal-combustion residues as fill: materials characterization for a test at Forsythe-Energy #5: Proceedings for the 14th Annual Abandoned Mined Land Conference, New Trends - Utilization of Recycled Materials and Waste Products in Mine Reclamation. (Chicago, Ill., August 23-27, 1992)

Paul, B., S.P. Esling, S. Chaturvedula, S. Chatterjee and F. Pisani 1993. Use of coal-combustion by-products as structural fill in reclamation: impacts on groundwater: p. 201-217. Proceedings of the NMLRC Symposium. (Collinsville, Ill., April 20-22, 1993) (Y. P. Chugh and D. C. Davin, editors).

Paul, B. and S.P. Esling 1994. Use of FGD by-products as a substitute fill material in mine reclamation - preliminary assessment of groundwater impacts: Proceedings of the Management of High Sulfur Coal-combustion Residues: Issues and Practices, (Springfield, Ill., April 5-7, 1994).

Prickett, T.A., T.G. Naymik and C.G. Lonnquist 1981. A 'random walk' solute transport model for selected groundwater quality evaluations. Illinois State Geological Survey, Bulletin 65, 103 p.

Pryor, W. A. 1956. Groundwater Geology in Southern Illinois: A Preliminary Geologic Report. Illinois State Geologic Survey Circular 212 (Urbana, Ill.) 25 p.

Rai, D., J.M. Zachara, D.A. Moore, K.M. McFadden and C.T. Resch 1989. Field investigation of a flue gas desulfurization (FGB) sludge

disposal site. Electric Power Research Institute, EPRI EA-5923, Project 2485-8.

Rehage, J.A. and L.J. Holcombe 1990. Environmental performance assessment of coal ash use sites: Little Canada structural ash fill. Electric Power Research Institute, EPRI EN-6532, Project 2796-1.

Sakata, Masahiro 1987. Movement and neutralization of alkaline leachate at coal ash disposal sites. Environmental Sciences and Technology, 21: 771-777.

Simsiman, G.V., G. Chesters and A.W. Andren 1987. Effect of ash disposal ponds on groundwater quality at a coal-fired power plant. Water Research 21 (4): 417-426.

Stone, R. and D.F. Snoeberger 1977. Cleat Orientation and Areal Hydraulic Anisotropy of a Wyoming Coal Aquifer. Groundwater 15: 434-438.

Stoner, J. 1981. Horizontal Anisotropy Determined by Pumping in Two River Basin Coal Aquifers, Montana. Groundwater 19: 34-40.

Theis, T.L. and K.H. Gardner 1990. Environmental assessment of ash disposal. Critical Reviews in Environmental Control 20 (1): 21-42.

Theis, T.L. and J.J. Marley 1979. Environmental considerations for fly ash disposal. America Society of Civil Engineers, Journal of the Energy Division 105 (EY1) January: 47-61.

Theis, T.L., J.D. C.L. Westrick Hsu and J.J. Marley 1978. Field investigation of trace elements in groundwater from fly ash disposal. Journal of Water Pollution Control Federation: 2457-2469

U.S. Waterways Experiment Station 1979. Effects of flue gas cleaning waste on groundwater quality and soil characteristics. U.S. Environmental Protection Agency, EPA-600/2-79-164, Municipal Environment Research Laboratory (Cincinnati, Ohio) 117 p.

USEPA 1986. RCRA Groundwater Monitoring Technical Enforcement Guidance Document. U.S. Environmental Protection Agency, Office of Waste Programs Enforcement, Office of Solid Waste and Emergency Response, OSWER-9950.1.

Villaume, J.F., L.E. Lang and J.A. Ripp 1983. Water balance at a compacted fly ash fill: Proceedings of the Characterization and Monitoring of the Vadose Zone. National Water Well Association.

Walton, W.C. 1985. Practical Aspects of Groundwater Modeling. Second Edition, National Water Well Association (Worthington, Ohio) 588 p.

Willman, H. B., E. Atherton, T. C. Buschbach, C. Collinson, J. C. Frye, M. E. Hopkins, J. A. Lineback and J. A. Simon 1975. Handbook of Illinois Stratigraphy. Illinois State Geological Survey Bulletin 95 (Urbana, Ill.) 261 p.