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.

Proceedings America Society of Mining and Reclamation, 1996 pp 87-95

DOI: 10.21000/JASMR96010087

https://doi.org/10.21000/JASMR96010087

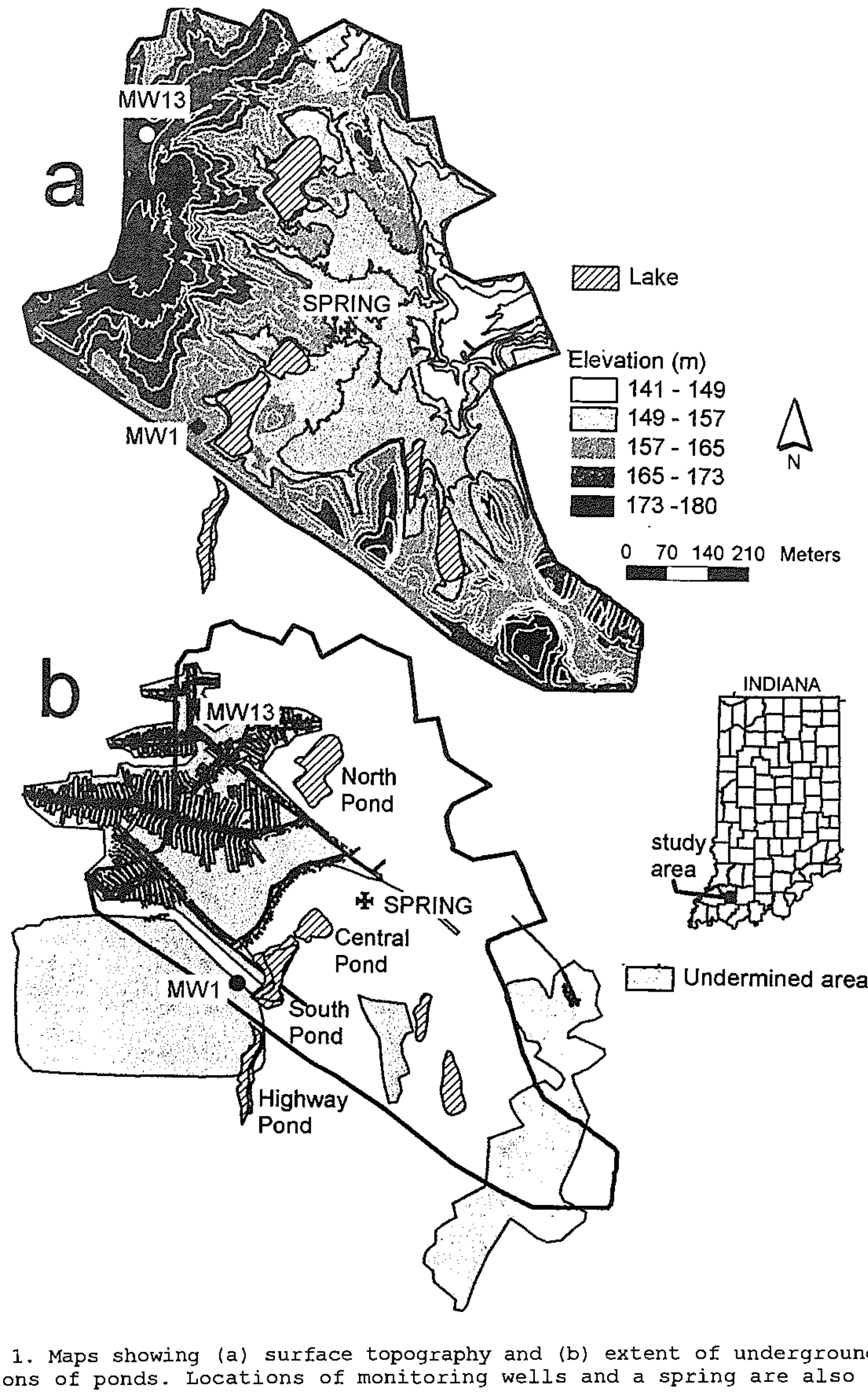

Figure 1. Maps showing (a) surface topography and (b) extent of underground mines and locations of ponds. Locations of monitoring wells and a spring are also shown.

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

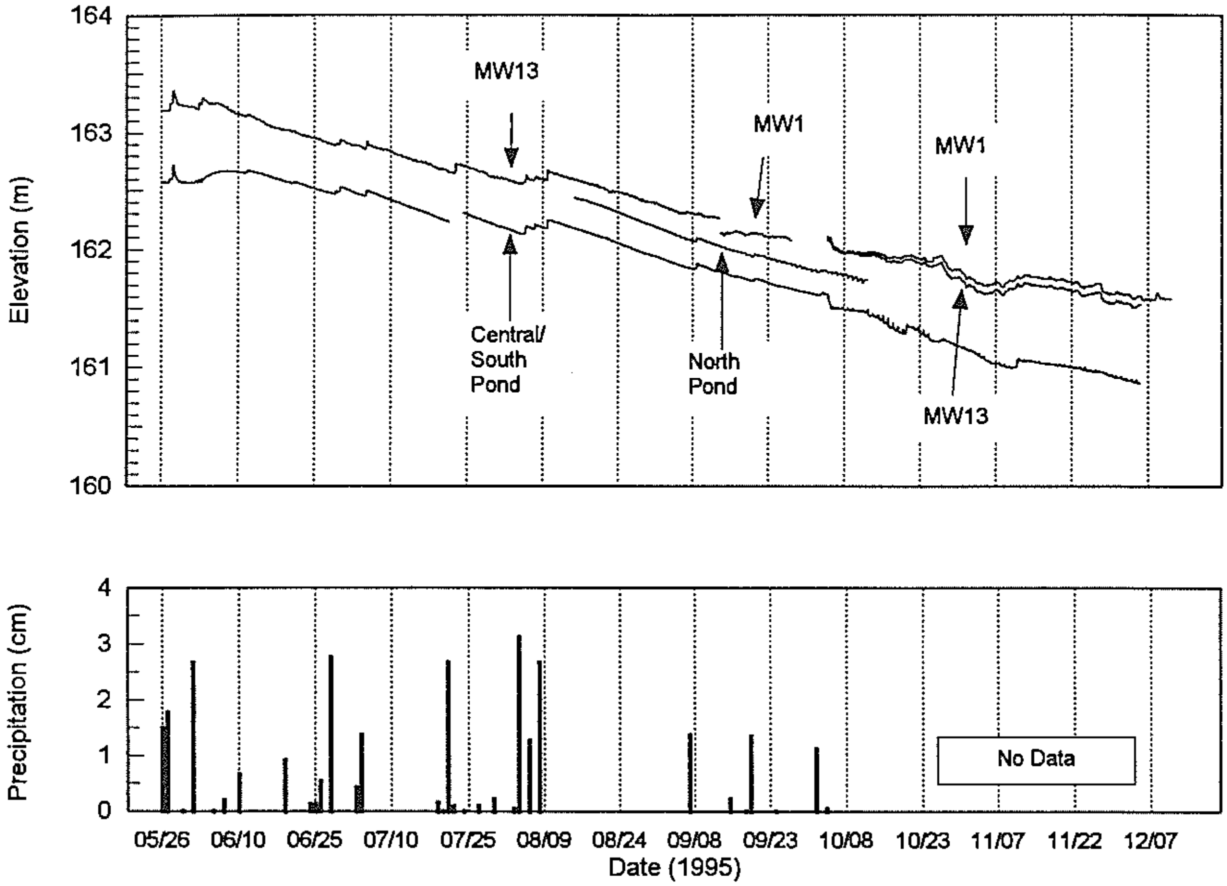

Figure 2. Graphs showing water levels and precipitation during the period of monitoring. Locations of monitoring sites are indicated in figure 1. Vertical grid lines indicate 00:00 AM.

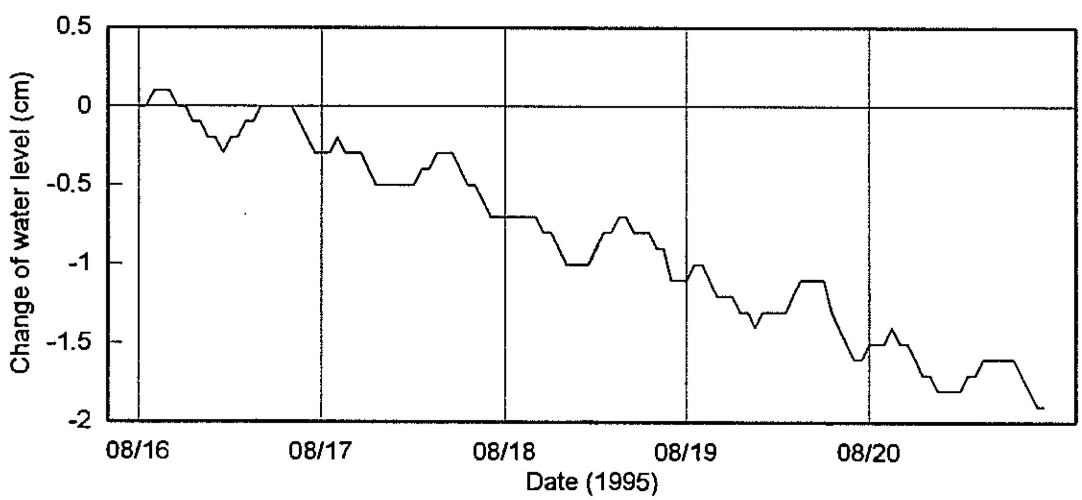

Figure 3. Graph showing daily cycles of water level observed in MW13 during a rainless period in August, 1995. The Y-axis shows the change in water level from its initial value. Vertical grid lines indicate 00:00 AM.

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:

$$S=\frac{n\gamma b}{EB} \tag{1}$$

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), 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:

$$S=\frac{\Delta V}{A\Delta h} \tag{2}$$

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

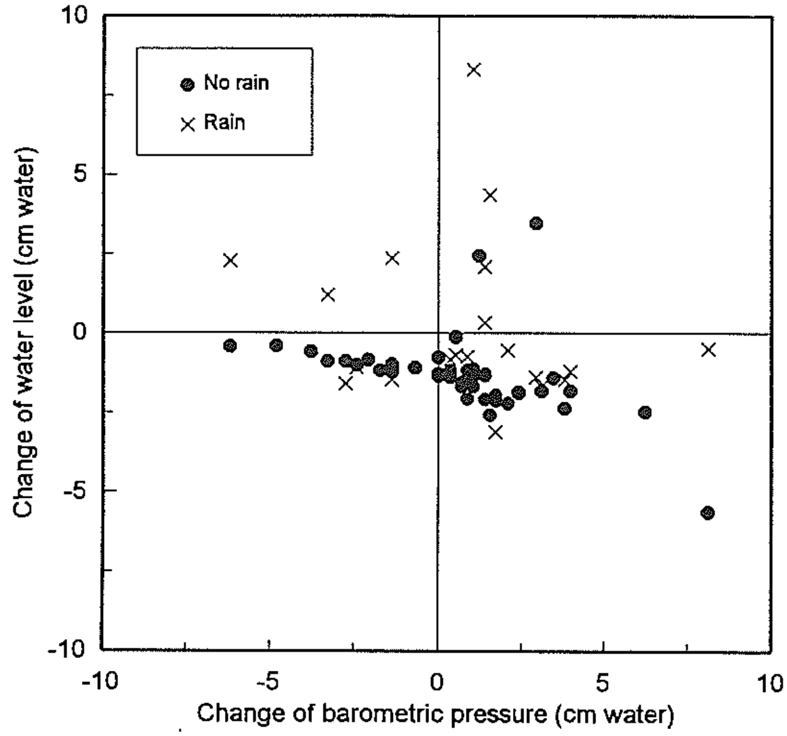

Figure 4. Plot of daily changes in water level of MW13 versus daily changes of atmospheric pressure.

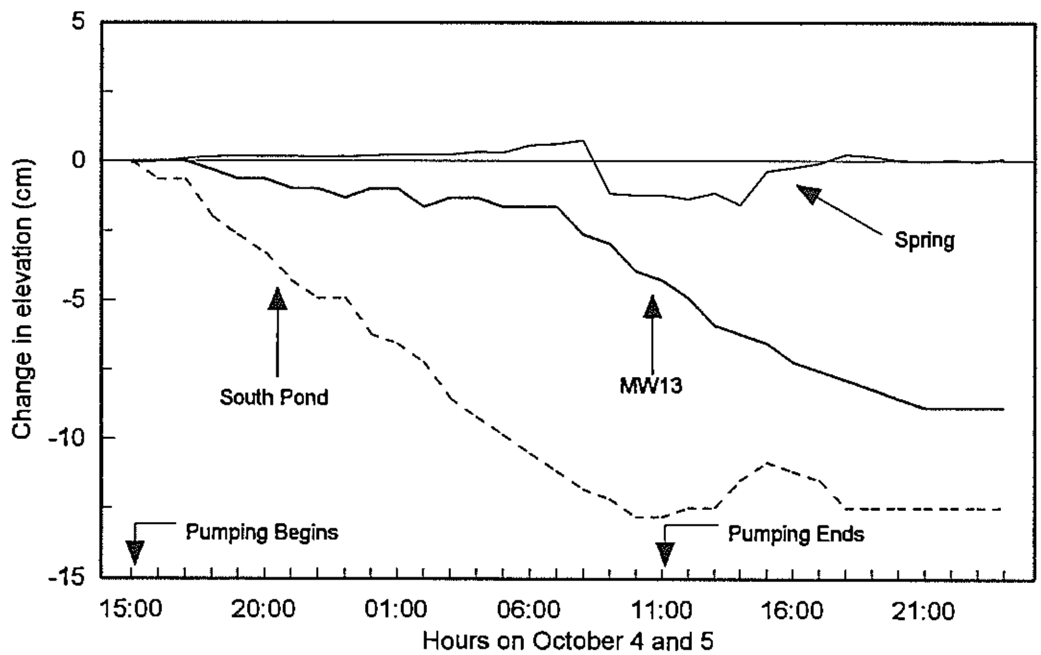

Figure 5. Response of water levels in MW13 and the South Pond during the pump test conducted on October 4 and 5, 1995. The spring's change of stage is also shown.

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 b_2) 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.