Journal of Hydrology, 146 (1993) 49–71
Elsevier Science Publishers B.V., Amsterdam

[2]

Statistical evaluation of hydrologic conditions in the vicinity of abandoned underground coal mines around Cannelburg, Indiana

Denver Harper[a] and Greg A. Olyphant[b]

[a]*Indiana Geological Survey, 611 N. Walnut Grove, Bloomington, IN 47405, USA*
[b]*Department of Geological Sciences, Indiana University, Bloomington, IN 47405, USA*

(Received 19 September 1992; revision accepted 2 December 1992)

ABSTRACT

Harper, D. and Olyphant, G.A., 1993. Statistical evaluation of hydrologic conditions in the vicinity of abandoned underground coal mines around Cannelburg, Indiana. J. Hydrol., 146: 49–71.

A statistical analysis of daily water-level changes in an abandoned coal mine indicates that precipitation affects the potentiometric level of the mine, independent of associated atmospheric pressure changes and changes in the water level of an overlying aquifer. The independent statistical effect of precipitation (0.99 cm of water-level change per centimeter of rainfall) is interpreted to reflect either lateral percolation from the coalbed's subcrop (1.2 km from the mine) or rapid recharge through mine-associated pathways, such as poorly plugged shafts, boreholes, or subsidence fractures. The relationship between water-level changes in the mine's voids and changes in the overlying aquifer is also statistically significant, but the regression coefficient (0.04) is an order of magnitude smaller than that for precipitation, indicating that vertical percolation (which is represented by covariance of the two aquifers) through undisturbed overburden may be less effective than the recharge associated with precipitation that bypasses the overburden. An equivalent analysis of water-level changes in an underlying unmined coalbed indicated that precipitation had a weaker direct effect (regression coefficient of 0.34, compared with 0.99), although it was still the dominant independent variable. In contrast, the effect of water-level changes in an overlying aquifer (the flooded mine itself) was relatively stronger (regression coefficient of 0.15, compared with 0.04), indicating that vertical percolation through interburden is more important at depth.

INTRODUCTION

Extensive areas of the United States are underlain by the flooded workings of shallow, abandoned coal mines. In many places, economically and environmentally important activities that have the potential to affect hydrologic conditions, such as surface mining, mine reclamation, methane recovery, and refuse disposal, are currently being conducted near such underground

Correspondence to: D. Harper, Indiana Geological Survey, 611 N. Walnut Grove, Bloomington, IN 47405, USA.

workings. Hydrologic changes have been implicated in mine subsidence and in contamination and dewatering of wells, yet little is known regarding the complex hydrogeologic setting of many abandoned underground mines.

In Cannelburg (Daviess County), Indiana, the vertical shaft of an abandoned underground mine collapsed in October 1989, and was filled in January, 1990, as an emergency action by the US Office of Surface Mining (OSM). In response to subsequent complaints of mine subsidence by nearby residents, the Indiana Division of Reclamation (DOR) in February 1990 requested that the Indiana Geological Survey Division (IGS) conduct an investigation of geologic and hydrologic conditions in the vicinity.

Our studies included analyses of short-term hydrologic responses to stresses (infiltrating rain and overburden loading), as well as more general consideration of hydrologic connections between the abandoned mine workings and surrounding strata. In this report we present a conceptual hydrologic model that was developed for the area, together with results of statistical tests of hypotheses regarding relationships among system components. Our main purpose is to evaluate evidence for the hypothesis that rainstorms cause changes in water levels at depth by rapid infiltration and percolation along pathways that bypass lithified overburden.

STUDY AREA

Mining history

The study area is partly underlain by the Buckeye and Mutual Mines, which were active between 1870 and 1913 in the Mariah Hill Coal Member of the Mansfield Formation (Morrowan Series, Pennsylvanian System) (Shaver et al., 1986), and which are separated by a narrow barrier of unmined coal (Ashley, 1899; Hutchison, 1971). Operating at depths of about 23–30 m, at an elevation of about 136 m above mean sea level, these mines produced a total of more than 6.9×10^5 metric tons of coal. About 0.66 km^2 (0.36 km^2 for the Buckeye Mine and 0.30 km^2 for the Mutual Mine) was undermined by room-and-pillar methods (Fig. 1).

There is no map that shows detailed workings of the Buckeye Mine, which is known to underlie much of the town of Cannelburg. Hutchison (1971) shows a generalized boundary of the mine, but his source is unknown. Similar, contemporaneous underground mines in nearby Montgomery (4 km west of Cannelburg) had openings that ranged in width from 7.6 to 11 m, pillars as narrow as 2.4–6.1 m, and local extraction ratios that ranged from 55 to 85% (Chugh, 1990). Estimates of areas underlain by voids and pillars yield an average extraction ratio of 57% for the Buckeye Mine (Harper et al., 1991).

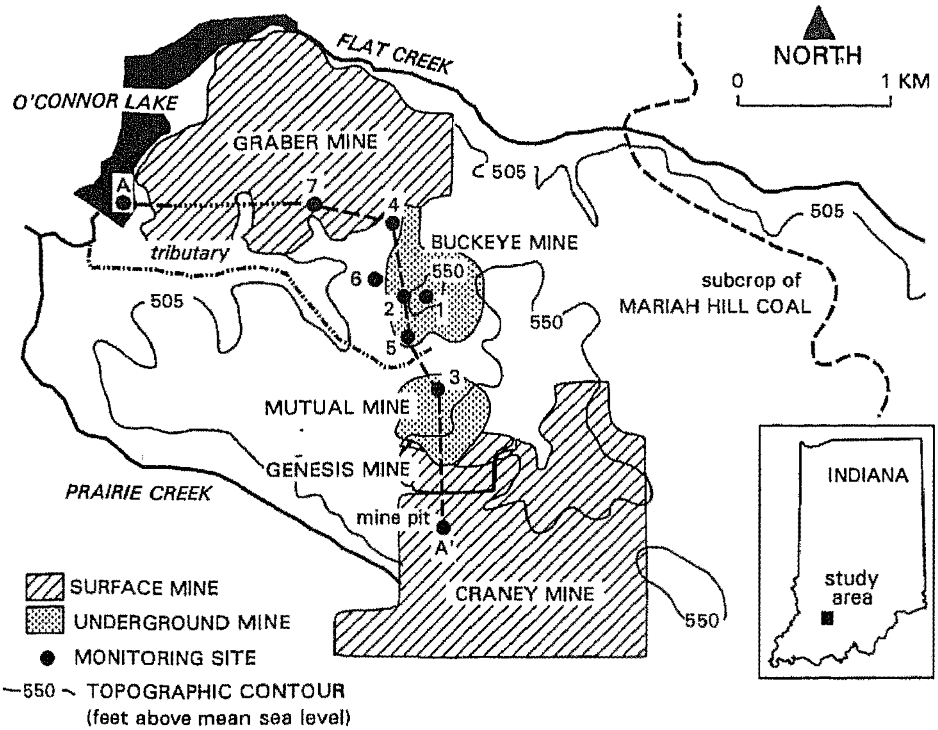

Fig. 1. Surface and underground mines and monitoring sites in the vicinity of the study area.

The underground mines are close to several recently active surface mines, which disrupted and displaced strata to create deposits of disturbed overburden (spoil). Such deposits of the Graber Mine (Fig. 1) extend down to a coalbed (Unit G) that underlies the Mariah Hill coal (Unit F, Fig. 2). In the early to mid-1980s, the miners encountered the northernmost workings of the abandoned Buckeye Mine, which they then partially dewatered by pumping. The Craney Mine, a surface mine active from the mid-1980s to present, is excavated to within about 240 m of the southern boundary of the Mutual Mine (Fig. 1). A large pit of the Craney Mine originally extended down to the Mariah Hill coal, but by summer, 1990, the pit had been backfilled with approximately 10 m of disturbed overburden (Fig. 2). The Genesis Mine apparently operated only in coalbeds above the Mariah Hill coal (Hasenmueller, 1986, 1991); in places, the Genesis Mine directly overlies the abandoned workings of the Mutual Mine (Fig. 2).

Geologic setting

Based on detailed observations in the Craney Mine pit, the unconsolidated

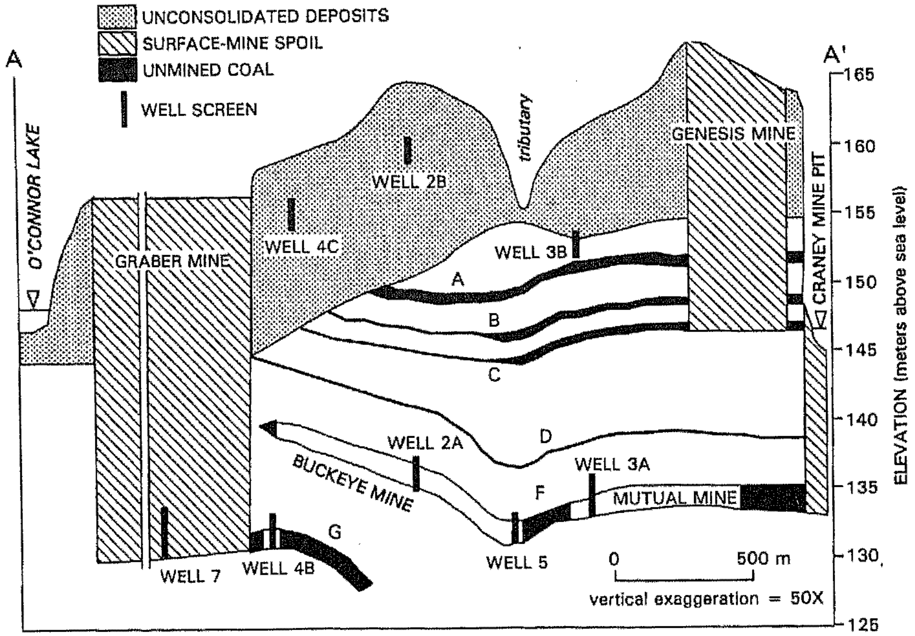

Fig. 2. Cross-section showing selected stratigraphic units and screened intervals of monitoring wells. See Fig. 1 for location.

materials can be categorized into four main groups (in descending stratigraphic order):

(1) Surficial loess of late-glacial (Wisconsinan) and recent age.

(2) A complex unit consisting of interbedded lake clays and sand or silts that is capped, in places, by ablation drift of late-Illinoian age. The water-laid sands and silts form locally confined aquifers with water levels that are often very close to the land surface.

(3) Basal till of Illinoian age that is generally dense and has low permeability but exhibits fractures in some exposures. Although present in most places, the till was presumably eroded away in the western part of the study area and replaced by alluvial deposits of sand, silt, and gravel.

(4) A truncated paleosol developed in silt and weathered shale of the Mansfield Formation that constitutes the upper part of the interburden between the surficial deposits and the Mariah Hill coal. Comparison of a gamma-ray log from a nearby borehole with gamma-ray logs from monitoring wells (Fig. 3) allowed recognition of similar units elsewhere in the study area.

In southwestern Indiana, on the eastern edge of the the Illinois Basin,

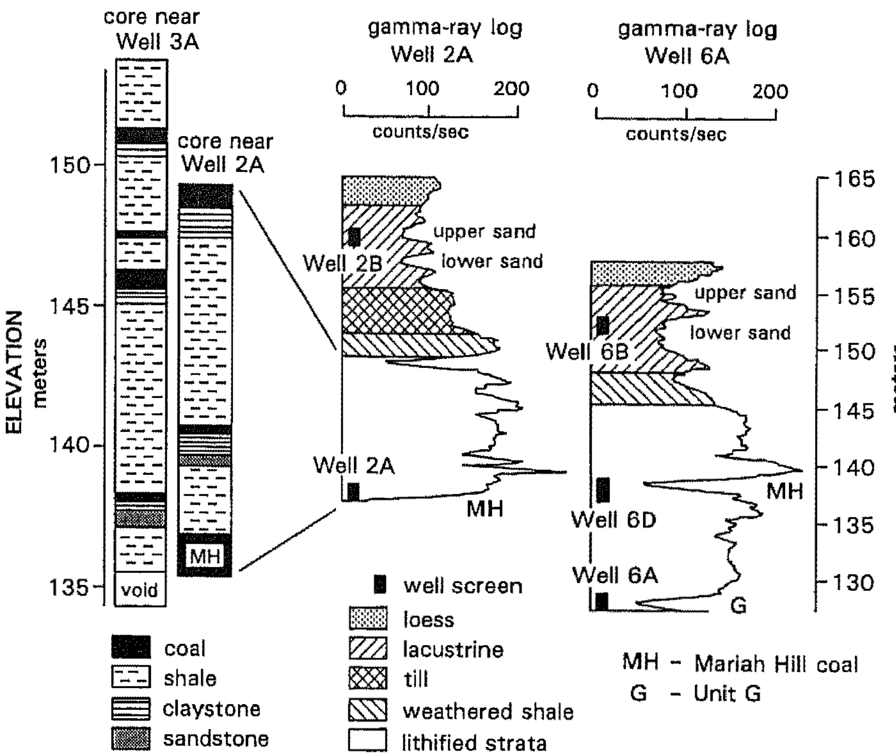

Fig. 3. Lithologic columns and gamma-ray logs from selected sites.

sandstones and coalbeds are the principal bedrock aquifers of Pennsylvanian age. The sandstones, which may be as much as 50 m thick, are typically fine grained, well cemented, and discontinuous; the coalbeds are typically thin (< 1.8 m thick) and sometimes discontinuous. Comparison of driller's logs and core descriptions with gamma-ray logs (Fig. 3) allowed correlation of several coalbeds across most of our study area. Sandstones and coalbeds are typically interbedded with aquitards such as shales, underclays, and limestones (Wangsness et al., 1981; Cocroft, 1984).

The presence of underground and surface mines and associated features (poorly plugged shafts and boreholes, subsidence fractures, and surface-mine pits) compounds the natural geologic complexity of the study area. Abandoned boreholes that were formerly used for mine ventilation, drainage, or electrical systems and that are unsealed or poorly sealed are scattered throughout southwestern Indiana; such features may be avenues for the vertical exchange of water. Subsidence sags and sinkholes are also common above shallow mines, but the distribution, characteristics, and continuity of

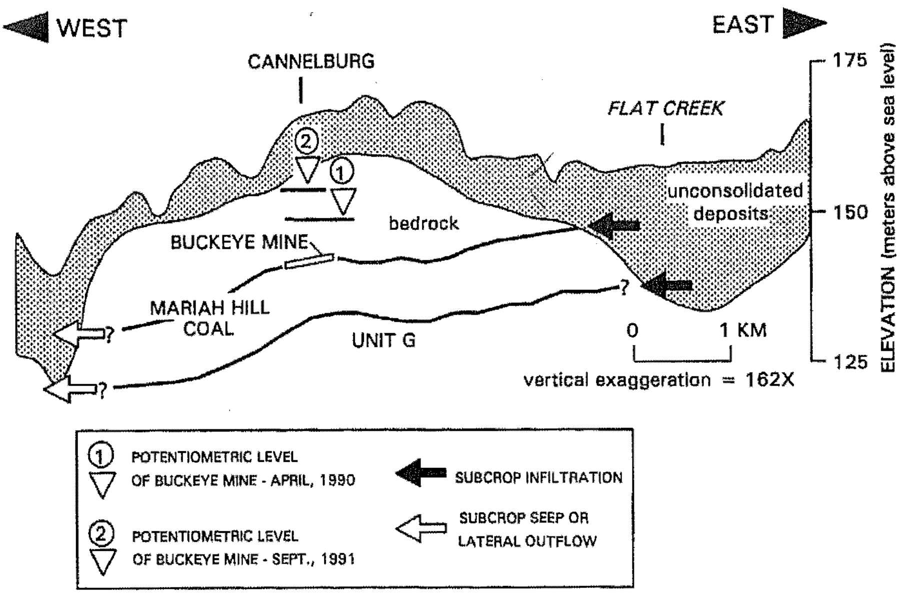

Fig. 4. Generalized cross-section showing the relationship of the Buckeye Mine and its potentiometric level to the ground surface and the bedrock surface. Modified from Hutchison (1971).

associated fractures are very poorly known. The development of fractures in overburden may depend on the relative abundance in the stratigraphic column of soft and pliable rocks (such as shales) and hard and brittle rocks (such as sandstones and limestones), with an increased probability of fractures where the latter are more abundant (Bauer, 1984). Cores of the lithified overburden of the Mutual and Buckeye Mines consist mostly of shales and claystones (88%); the remainder consists of coal (8%) and sandstone and limestone (4%).

There is a regional southwestward component of groundwater flow in bedrock toward the center of the Illinois Basin (Wangsness et al., 1981), but in shallow, undisturbed settings, local groundwater flow is predominantly toward major streams. East of the Mutual and Buckeye mines, the Mariah Hill coal subcrops beneath alluvial deposits in the bedrock valley of Flat Creek (Figs. 1 and 4), which is impounded by the O'Connor Flood Control Dam at a pool elevation of 147.5 m above sea level, and whose headwaters lie about 4 km east of the Mutual Mine at an elevation of about 154 m above sea level. In the unmined area west of the Buckeye and Mutual Mines, Hutchison (1971) does not depict the Mariah Hill below an elevation of about 128 m, but his cross-section indicates that the coalbed may subcrop in a deep bedrock valley, whose axis passes about 2.4 km west of the study area (Fig. 4).

TABLE 1

Installation of monitoring wells

Well	Surface elev. (m)	Depth to top of screen (m)	Screen length (m)	Comments
Wells installed in unconsolidated materials				
2B	165	4.6	1.5	Flowing sand
4C	159	4.0	1.5	Silty clay
6B	158	4.9	1.5	Sand/gravel
7	156	23.9	3.0	Disturbed strata of surface mine
Wells installed in rock strata				*Stratigraphic unit*[a]
1B	169	19.2	1.2	A (unmined)
2A	165	27.7	1.5	F (mine void)
3A	164	27.4	3.0	F (mine void)
3B	164	11.3	1.5	Shale
4B	159	27.4	1.8	G (unmined)
5	158	25.3	1.5	F (mine void)
6A	158	28.7	1.5	G (unmined)
6C	157	18.3	1.2	F (unmined)
6D	158	19.5	1.8	F (unmined)

[a] See Fig. 2.

WELL INSTALLATIONS AND HYDROLOGIC TESTS

Table 1 summarizes the depths of 13 monitoring wells that were installed for the study and the stratigraphic units in which the wells were screened. During the installation of each monitoring well, the annular space between the casing and the borehole was sealed by pressure grouting with slurried bentonite. In addition, two boreholes were left temporarily uncased (Wells 1A and 4A), except in surficial unconsolidated materials, so that rock strata in the holes could be inspected later by use of a borehole television camera.

Well 2B was screened in a thin (< 1 m) layer of fine-grained sand and silt that is underlain by less permeable and more cohesive silt and clay (Fig. 3). Well 6B was screened in a thin (< 1 m) layer of fine sand with some gravel; the unit is underlain by less permeable silt and clay. Both of the shallow aquifers are confined by capping layers of silty clay and have potentiometric surfaces in the surficial loess.

With respect to the abandoned underground mines, the guiding concept of our drilling program was to install monitoring wells in voids of each of the mines, in the barrier between the mines, and in the unmined coalbed to the west and north of the Buckeye Mine. We succeeded in every respect except one: in our attempt to install a well in the barrier between the mines, we encountered a void of the Buckeye Mine instead. Four boreholes encountered intact voids of the Buckeye and Mutual mines (Wells 2A, 3A, and 5, and a core hole near Well 3A), one borehole penetrated a substantially intact pillar that showed evidence of slight crushing (a core hole near Well 2A), and one borehole may have penetrated a thoroughly crushed pillar (Well 4A). At Well 1A, roof strata may have collapsed to a height of as much as 3 m above the original void. Two boreholes penetrated unmined Mariah Hill coal that lies outside the Buckeye Mine (Wells 6C and 6D).

In addition to our monitoring wells in the mines and the surrounding Mariah Hill coal, two boreholes penetrated an unmined coalbed (Unit G) that underlies the Mariah Hill coal (Wells 4B and 6A). A well was successfully installed in an unmined coalbed that overlies the Mariah Hill coal (Well 1B) but subsequently became plugged for unknown reasons. Well 7 was installed near the bottom of the deposit of disturbed overburden of the Graber Mine, which operated in both the Mariah Hill coal and Unit G.

Changes of water levels in wells were measured in increments of 0.305 cm (0.01 ft) and recorded using Druck pressure transducers and Omnidata (Datapod II) dataloggers. For these routine measurements, the data loggers were programmed to record the average of four values measured at 15 min intervals during the preceding hour. Total hourly precipitation was measured near Well 3A (using a tipping-bucket rain gauge), and atmospheric pressure was measured hourly with an electronic transducer during the last 111 days of the study.

A mechanical chart recorder was installed to monitor the level of water in the Craney Mine pit (Figs. 1 and 2). In September 1990, when the mine operator resumed filling part of the pit with earth, the water began rising irregularly. Soon thereafter, when the pit received runoff from a storm, the chart recorder was inundated, and we were unable to continue monitoring.

Slug tests were performed on wells installed in unconsolidated materials, unmined coalbeds, and a surface-mine deposit. Hydraulic conductivities, summarized in Table 2, were estimated by the method of Thompson (1987). Hydraulic conductivities of the unmined Mariah Hill coal (Wells 6C and 6D) were comparable with values for the underlying coalbed (Wells 4B and 6A in Unit G) and for the water-bearing sands in the unconsolidated deposits (Wells 2B and 6B), but were significantly greater than the value for an overlying coalbed (Well 1A in Unit A). Shale in the uppermost bedrock (Well 3B) and the deposit of disturbed overburden of the Graber Mine (Well 7) had the lowest conductivity values.

The storage and transmissive characteristics of the flooded underground mine voids were evaluated by a series of injection tests, in each of which about

TABLE 2

Hydraulic conductivity[a] (K)

Well	Unit	K (cm s^{-1})
Unconsolidated units and disturbed overburden		
2B	Upper sand	3×10^{-4}
4C	Sandy clay	1×10^{-4}
6B	Middle sand	1×10^{-3}
7	Surface mine	$<1 \times 10^{-5}$
Unmined coalbeds and bedrock		
1A	A[b]	7×10^{-5}
3B	Shale[b]	$<1 \times 10^{-5}$
4B	G[b]	1×10^{-3}
6A	G[b]	3×10^{-3}
6C	F[b]	6×10^{-4}
6D	F[b]	4×10^{-3}

[a] Calculated by the method of Thompson (1987).
[b] See Fig. 2.

7570 l (2000 gallons) of water were introduced into a mine by gravity drainage, and simultaneous changes of water levels were recorded in observation wells at intervals of 10 s. Our estimated value of storativity for the mine aquifer (2.6×10^{-4}) is in the lower part of the range for confined aquifers reported in Freeze and Cherry (1979).

TEMPORAL CHANGES OF WATER LEVELS

Except for very small (< 1 cm), transient differences during rainstorms, the elevations of water in Wells 2A, 3A, 5, 6C, and 6D, all of which were screened in mine voids or unmined coal, were essentially equal throughout our investigation (Fig. 5). On 26 April 1990, the potentiometric level of the mine voids was at an elevation of 148.91 m, or about 13.4 m above the roof of the abandoned mines. Subsequently, the potentiometric levels of the mine voids rose irregularly; periods when levels were rising rapidly alternated with periods when water levels were relatively stable. By 1 January 1992, the water in Well 2A stood at an elevation of 154.35 m, or about 5.44 m higher than when the investigation began.

The records of water levels in Wells 2B and 6B, in unconsolidated overburden, exhibit transient responses to rainstorms superimposed on seasonal fluctuations (Fig. 5). Although water levels in Wells 2B and 6B change similarly, the elevation of water in Well 6B has always been lower, and,

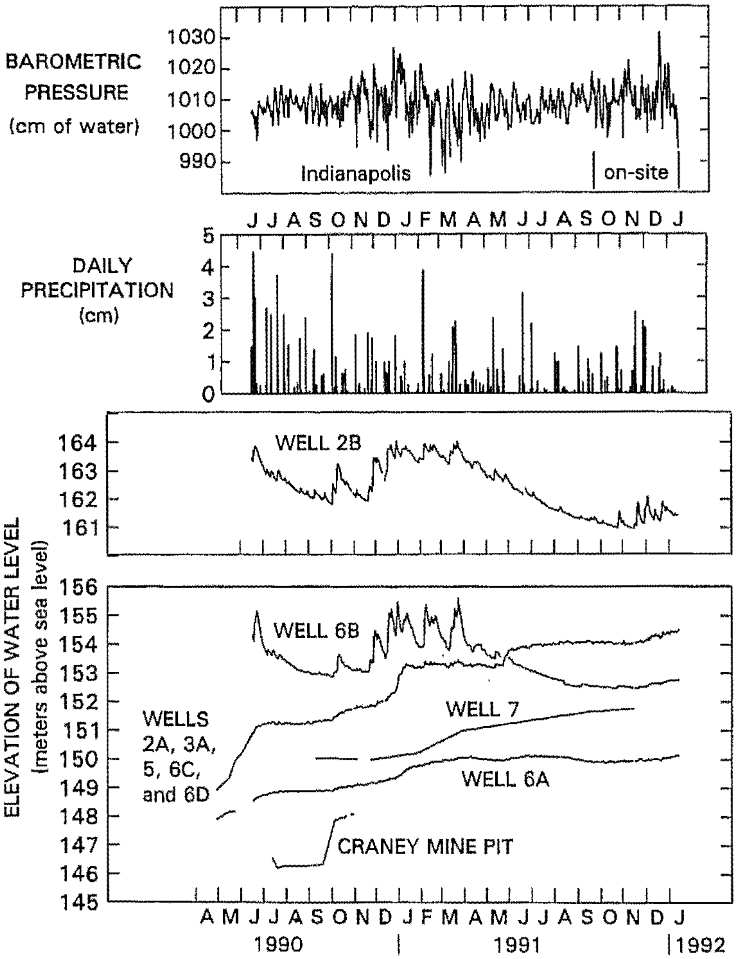

Fig. 5. Average daily atmospheric pressure, total daily precipitation and average daily water levels at various monitoring sites in the study area.

near the end of our investigation, it fell below the potentiometric level of the mine aquifer (Fig. 5).

Soil moisture was measured weekly near Well 2B using a neutron probe. Analysis of cores indicates that porosity of the loess is approximately 0.4 at depth and 0.45 near the surface. Moisture content at shallow depths (0.3 m) is highly variable, ranging from a maximum of 0.45 after winter storms to less than 0.15 during late summer, whereas moisture content at greater depth (3.7 m) remains near saturation throughout the year (Fig. 6). Water that percolates into the deeper part of the unsaturated zone may be moving

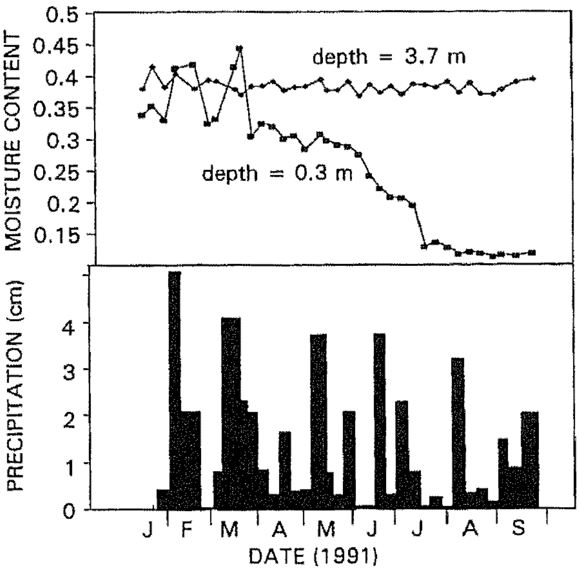

Fig. 6. Soil moisture in the unsaturated zone near Well 2B (upper), and total precipitation during intervals between soil-moisture measurements (lower). Saturated moisture content at a depth of 3.7 m is approximately 0.4.

laterally across the contact with the lacustrine silty clay, until it establishes a vertical connection with underlying sand aquifers.

The water in Well 6A, in the unmined coalbed that underlies the Buckeye Mine, rose throughout our investigation (Fig. 5), but the difference between the elevations of the water levels in Wells 6A and 2A increased. If the average rates at which elevations changed throughout the entire period are extrapolated into the past, then the potentiometric level of the Mariah Hill coal would have been the same as that of Unit G in April 1989 (181 days before the study commenced).

CONCEPTUAL HYDROLOGIC MODEL

Figure 7 is a simplified conceptual model of the hydrogeologic system around Cannelburg, Indiana. The ultimate source of all natural recharge to the Mutual and Buckeye mines is rainfall, which infiltrates surficial unconsolidated deposits, including soil, glacial deposits, surface-mine deposits, and alluvium of local stream valleys.

Water stored in surficial unconsolidated units may percolate through undisturbed lithified overburden of the Mariah Hill coal, or recharge to the mines could conceivably occur through shafts, boreholes, sinkholes, joints, or

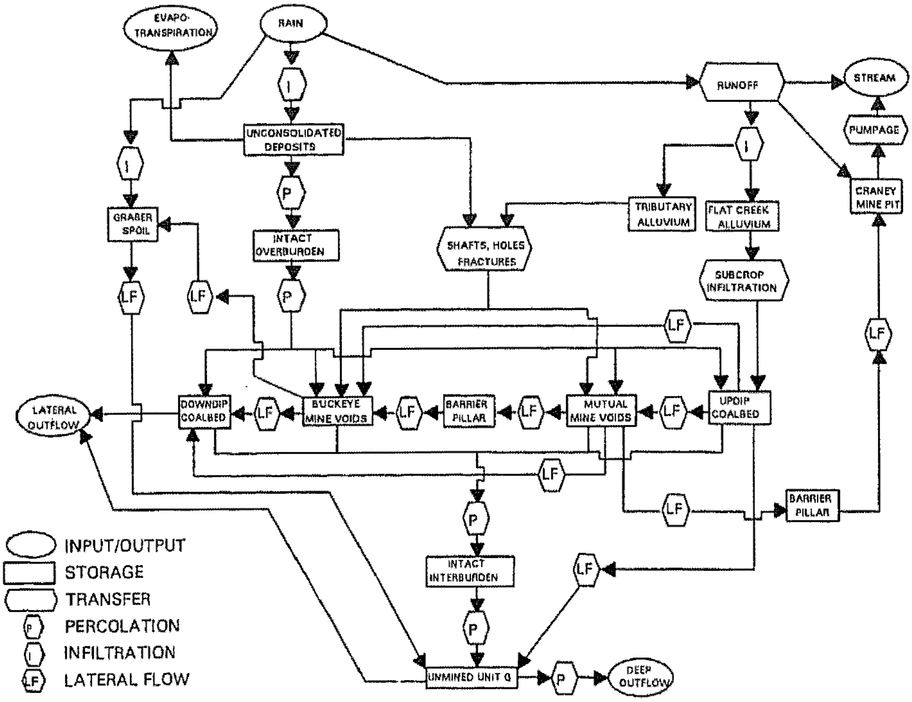

Fig. 7. Diagram showing components of a hypothetical model representing hydrologic conditions in the vicinity of Cannelburg, Indiana.

subsidence fractures in the bedrock (Fig. 7). The shafts of neither the Buckeye nor Mutual mines are situated to receive surface runoff, but they might serve to conduct water from shallower to deeper units. We are unaware of any abandoned boreholes into the mines, but, in the absence of mine maps, it is possible that there are undiscovered boreholes that are no longer exposed at the surface or that are located in obscure areas such as woodlots and hedgerows. Several features that may be subsidence sags exist in the study area, but the predominance of shale in the geologic column and the absence of sinkhole-type subsidence are indications that subsidence fractures — if they exist at all — are probably narrow and discontinuous. Nevertheless, their existence can not be ruled out. Any undetected subsidence fractures along the small, intermittent tributary that passes near the southern part of the Buckeye Mine might provide a direct, vertical flowpath that bypasses the surficial deposits of loess and till (Fig. 2).

Recharge of the Mutual and Buckeye mines may also occur by lateral flow through unmined coal from the subcrop of the Mariah Hill coal (Fig. 7). Discharge from the mines may occur by lateral flow to disturbed deposits of the Graber Mine, to the coalbed's subcrop, and to the Craney Mine pit, or may occur by percolation downward, through the shaley interburden between the Mariah Hill coal and Unit G (Fig. 7). However, because there are no abandoned underground mines in Unit G, direct flowpaths by way of shafts, boreholes, and subsidence fractures should not exist in that interval. From Unit G, water could be discharged by vertical percolation downward, or by lateral flow through the unmined coal, as already discussed for the Mariah Hill coal.

STATISTICAL METHODS AND DATA ANALYSIS

The data used in our analyses are time series of average daily water levels, average daily atmospheric pressure, and total daily precipitation. Thus, there is probably strong autocovariance between measured attributes that may not necessarily reflect cause-and-effect relationships (Ostrem, 1978). Autocorrelation of error terms in regression equations and other complicating effects, such as changes caused by overburden loading, can complicate any statistical analyses that are conducted. With respect to overburden loading, for example, changes of the potentiometric level of a confined aquifer may have a strong relationship (expressed as the aquifer barometric efficiency) to changes of atmospheric pressure. Hourly measurements of local atmospheric pressure that were made during the last 111 days of the investigation indicate that the barometric efficiency of the mine aquifer is 67%. A cross-correlation between pressure changes recorded at the study site and changes recorded at the weather station of the National Oceanic and Atmospheric Administration (NOAA) in Indianapolis, Indiana, indicates that there is no statistical difference between pressure measurements at the two sites (the regression coefficient is not statistically different from unity and the coefficient of determination is 0.97). Therefore, the use of pressure data from the Indianapolis weather station in subsequent statistical analyses is justified.

Underlying the statistical regression procedures that we have employed is the assumption that linear relationships exist between various storages of our conceptual model (Fig. 7). The assumption of linear relationships is plausible, because all of the measured attributes have the simple dimension of length: potentiometric levels are expressed as elevations above sea level in meters, whereas precipitation, changes of water levels, and changes of atmospheric pressure are expressed in centimeters of water.

Because the usual assumption of random error terms in linear relationships is not justified in the case of our time-series data, we have utilized generalized least squares and employed an iterative procedure to converge on a best-fit set of parameters under the more realistic assumption that error terms in the linear equations are autoregressive.

Average daily water levels

Parameter estimates and associated standard errors for linear equations that relate water levels in monitoring wells installed in the Mariah Hill coal and its mines are given in Tables 3(a) and (b). The regression coefficient that relates the water levels in the two wells within the Buckeye Mine (Wells 2A and 5) is unity, and the intercept is not statistically different from zero at the 95% confidence level (Table 3(a)). Similarly, regression coefficients that relate the water level in the Buckeye Mine (Well 2A) to levels in the unmined coalbed immediately west of the mine (Wells 6C and 6D) are not statistically different from unity at the 95% confidence level (Table 3(b)), and the equations' intercepts are not significantly different from zero. In contrast, coefficients that relate the water level in the Buckeye Mine (Wells 2A and 5) to the level in the Mutual Mine (Well 3A) are less than unity (Table 3(a)). The *t*-ratios for a null hypothesis that the slopes are not statistically different from unity (3.00 and 2.88, respectively) indicate that the null hypothesis can be rejected (95% confidence level) in both instances. Also, the intercepts of both regression equations are statistically different from zero at the 95% confidence level (Table 3(a)).

Statistical results that relate water levels in different stratigraphic units to water levels in voids of the Buckeye Mine are summarized in Table 3(c). A *t*-test of the regression coefficient that relates the water level in the Buckeye Mine (Well 2A) to the level in the underlying coalbed (Well 6A) indicates that the coefficient is statistically less than unity, and the intercept is statistically different from zero at the 95% confidence level (Table 3(c)). Nevertheless, the parameters relating water levels in the two units are statistically significant. Regression coefficients that relate the water level in the Buckeye Mine (Well 2A) to water levels in the two monitored layers of unconsolidated sands (Wells 2B and 6B) are both statistically less than unity, and their numerical values are very similar (Table 3(c)), but when the water levels in the sand layers were cross-correlated to test for equality of daily values, the regression coefficient was found to be significantly different from unity, although the intercept was not significantly different from zero at the 95% confidence level (Table 3(d)).

Daily changes of water levels

In our conceptual model, we suggest that direct hydrologic connections may exist between the ground surface and the mines, so that infiltrating

TABLE 3

Bivariate regression analyses of relationships between water levels in various monitoring wells at the study site[a]

Model: $Y_t = b_0 + b_1 X_t + (\rho e_{t-1} + v_t)$

(a) Relationships among mine voids

X	Y	n[b]	b_0[c]	b_1[c]	ρ[d]	t_1[e]
2A	5	76	−0.579 (1.669)	1.004 (0.011)	0.456	0.36
3A	5	76	6.961* (2.361)	0.954 (0.016)	0.522	2.88**
3A	2A	403	1.433* (0.405)	0.991 (0.003)	0.893	3.00**

(b) Relationships between Buckeye Mine void and unmined coal

X	Y	n[b]	b_0[c]	b_1[c]	ρ[d]	t_1[e]
2A	6C	94	−1.584 (1.118)	1.010 (0.007)	0.118	1.43
2A	6D	49	5.480 (5.513)	0.964 (0.036)	0.743	1.01

(c) Relationships between Buckeye Mine void, underlying coal, and overlying unconsolidated sand layers

X	Y	n[b]	b_0[c]	b_1[c]	ρ[d]	t_1[e]
2A	6A	510	104.27* (1.74)	0.295 (0.011)	0.999	64.09**
2B	2A	510	134.04* (2.230)	0.119 (0.014)	0.996	62.93**
6B	2A	510	137.51* (1.779)	0.103 (0.012)	0.996	74.75**

(d) Relationship between water levels in unconsolidated sand layers

X	Y	n[b]	b_0[c]	b_1[c]	ρ[d]	t_1[e]
2B	6B	510	8.286 (4.874)	0.894 (0.030)	0.945	3.53**

[a] Raw data are average daily values of water-level elevations in meters above sea level. Equation parameters b_0, b_1, and ρ were estimated using an iterative procedure outlined in (Kmenta, 1971, p. 288).
[b] Number of observations.
[c] Estimated regression parameters, and standard errors (in parentheses).
[d] Estimated serial autocorrelation coefficient.
[e] Calculated t-ratio for the null hypothesis that the regression coefficient (b_1) equals unity.
* Regression intercept is statistically different from zero at 95% confidence level.
** Null hypothesis that regression coefficient equals unity is rejected at the 95% confidence level.

TABLE 4

Multiple regression analysis of the relationship between changes of the water level in Well 2A (Buckeye Mine void), atmospheric pressure (B), precipitation (P), and changes of the water level in Well 6B (lower sand layer) at the study site[a]

Model: $\Delta 2A_t = b_0 + b_1 \Delta B_t + b_2 P_t + b_3 \Delta 6B_t + (\rho e_{t-1} + v_t)$

n[b]	b_0[c]	b_1[c]	b_2[c]	b_3[c]	ρ[d]
540	0.429* (0.134)	−0.317* (0.020)	0.993* (0.186)	0.040* (0.010)	0.224

[a] Variables are expressed in centimeters of water. Regression parameters (b_0–b_3) and autocorrelation coefficient ρ were estimated using an iterative procedure outlined in (Kmenta, 1971, p. 288).
[b] Number of observations.
[c] Estimated regression parameters, and standard errors (in parentheses).
[d] Estimated autocorrelation coefficient.
* Regression parameter is statistically different from zero at 95% confidence level.

rainfall influences water levels in the mines, independent of the behavior of water levels in the next overlying aquifer. We have indirectly evaluated this hypothesized connection by statistically testing (within the framework of a multiple regression analysis) the effect that precipitation has on water-level changes within the Buckeye Mine, while controlling for the effect of water-level changes in an aquifer in the unconsolidated overburden. The correlation between precipitation and water-level changes in the mine is complicated by the mine aquifer's response to changes of atmospheric pressure, so that the latter have also been included in the multiple regression.

Each of the independent variables that were included in the analysis has a significant independent effect on water-level changes in the mine, as indicated by partial regression coefficients that are statistically different from zero (Table 4). In addition, the intercept is also statistically greater than zero, indicating a time-dependent rise in water levels that is independent of the variables that were included in the analysis. Because all of the variables are measured in centimeters, the relative importance of the independent variables can be evaluated by simply comparing the magnitudes of the regression coefficients: the effect of precipitation is about three times as large as the effect of atmospheric pressure changes, which is, in turn, about eight times as large as the effect of water-level changes in the unconsolidated sand layer. Note that, according to our regression analysis, the partial effect of atmospheric pressure changes on water-level changes in the Buckeye Mine is only about half of the barometric efficiency reported above.

TABLE 5

Multiple regression analysis of the relationship between changes of the water level in Well 6A (unmined Unit G), atmospheric pressure (B), precipitation (P), and changes of the water level in Well 2A (Buckeye Mine void) at the study site[a]

Model: $\Delta 6A_t = b_0 + b_1 \Delta B_t + b_2 P_t + b_3 \Delta 2A_t + (\rho e_{t-1} + v_t)$

n[b]	b_0[c]	b_1[c]	b_2[c]	b_3[c]	ρ[d]
540	0.115* (0.039)	−0.112* (0.007)	0.340* (0.055)	0.148* (0.013)	0.173

[a] Variables are expressed in centimeters of water. Regression parameters (b_0–b_3) and autocorrelation coefficient ρ were estimated using an iterative procedure outlined in (Kmenta, 1971, p. 288).
[b] Number of observations.
[c] Estimated regression parameters, and standard errors (in parentheses).
[d] Estimated autocorrelation coefficient.
* Regression parameter is statistically different from zero at 95% confidence level.

As an extension of the above analyses, we conducted a multiple regression analysis to evaluate statistically the effect that precipitation has on water-level changes within the underlying unmined coalbed (Unit G), while controlling for atmospheric pressure changes and for water-level changes in the Buckeye Mine (Table 5). The partial effect of precipitation is three times greater than the effect of atmospheric pressure, although the coefficient of precipitation for water-level changes in Unit G is only about one-third as large as that for water-level changes in the Buckeye Mine (compare Tables 4 and 5). Also in contrast to Table 4, the partial effect in Table 5 of the overlying aquifer (the flooded Buckeye Mine itself) is stronger than the partial effect of atmospheric pressure changes, either because of Unit G's lower barometric efficiency or because percolation through the interburden between the mine and Unit G is greater (Table 5). The equation's intercept, which is also signficantly greater than zero, is less than one-third as large as that of the mine (compare Tables 4 and 5), indicating that whatever causes the long-term rise operates more effectively on the Buckeye Mine than on Unit G.

DISCUSSION

In our conceptual model of hydrologic conditions at the study area (Fig. 7), we hypothesize that numerous mechanisms of vertical and lateral recharge may be operating on the mine aquifer. Such hypotheses are very difficult to evaluate, given available methods of monitoring. In lieu of a more rigorous, physically based approach, we utilize statistical inference to evaluate certain critical relationships that are included in the conceptual model. Although a statistically significant linear relationship between variables demonstrates neither cause-and-effect nor physical flow, we believe such correlations to be indicative of some underlying process.

Lateral relationships

The water levels within two wells of the Buckeye Mine (Wells 2A and 5), located 378 m apart, remained equal (Table 3(a)), indicating that there is relatively little restriction to flow within the interconnected voids of the Buckeye Mine. Such conduit flow is also indicated by the results of injection tests: when water was introduced into either well, the water level in the other exhibited a measurable response only 90 s after the injection commenced.

Water levels in Wells 6C and 6D, which are located near the Buckeye Mine's western boundary, also remain similar to the level in the mine, and from a statistical standpoint, change in 1:1 correspondence (Table 3(b)). Thus, a good hydrologic connection seems to exist between the Buckeye Mine and the area of unmined coal adjacent to the western boundary. This finding is corroborated by results of our injection tests: during an injection into Well 2A, a measurable response of Well 6D occurred within about 2 min and was similar in form to that of Well 5. During and immediately following rainstorms, however, the water level in Well 2A exhibits slightly larger transient responses than the level in Well 6D. This may indicate the existence of slightly greater recharge in the area of the mine and lateral flow from the mine that is directed outward (westward) along its western boundary.

A slight, but statistically significant, difference exists between the time trends of water levels in the Buckeye Mine (Wells 2A and 5) and the Mutual Mine (Well 3A). This difference exists despite the fact that the two mines are separated by a barrier of unmined coal that we estimate to be only about 174 m wide. The quicker and slightly amplified response of the Mutual Mine to rainstorms may indicate the existence of more numerous, or more permeable, recharge pathways into that mine.

In our initial reconnaissance of the study area, we considered the Craney Mine pit to be a potential recharge area for the Mutual Mine: water percolating vertically through the earthen fill of the pit might flow laterally through an intervening barrier of unmined coal (about 240 m wide), and thereby enter the abandoned workings (Fig. 2). Sufficient data are not available for proper statistical evaluation, but a comparison of water-level time trends indicates that the mine did not respond to the sudden, large rise (about 0.7 m) in the water level of the pit that occurred between 28 September and 3 October 1990 (Fig. 5) in response to in-filling of the pit. However, the water levels of both the mine and the pit responded to a large rainstorm that occurred on 3 October.

The water level in Well 7, installed in the Graber Mine's spoil, remained below the level of the Buckeye Mine (Fig. 5). The very low permeability of the spoil (Table 2) indicates to us that the deposit represents neither a significant recharge nor discharge pathway to either the Buckeye Mine or Unit G, although we recognize the variability of such material and the possibility that effective hydrologic pathways exist elsewhere in the deposit, undetected by us.

There may be lateral exchange of water between the underground mines and the alluvium of Flat Creek. The Mariah Hill coal is known to subcrop beneath the creek's alluvium, as close as 1.2 km northeast of the Buckeye Mine (Fig. 1); Unit G, whose hydraulic conductivity is comparable with that of the Mariah Hill coal (Table 2), may also subcrop beneath the alluvium, although at a greater distance from the Buckeye Mine and at a greater depth beneath the land surface (Fig. 4). At the beginning of our study, when the potentiometric level of the Buckeye Mine was at an elevation of about 148.9 m above sea level, there may have been lateral westward recharge from the coalbed's subcrop in the east, where the elevation of the ground around the headwaters of Flat Creek is about 153.9 m. By the end of our study, however, the water level of the mine workings was at about the same elevation as the creek's headwaters. In contrast, the water level of Unit G remained well below the elevation of Flat Creek near the subcrop of Unit G, so that recharge from the subcrop could have existed even in the late phase of monitoring.

Vertical relationships

The statistically significant relationship between water levels in Well 2A in the Buckeye Mine and in Well 6A in the underlying, unmined Unit G (Table 3(c)) indicates that either (1) vertical recharge of Unit G is derived from the Buckeye Mine through interburden, or (2) both units receive lateral recharge from some common source. With regard to the former, any such recharge probably occurs through intact bedrock, because there are no underground mines in Unit G, and, consequently, there can be no subsidence fractures or poorly plugged shafts.

The statistically significant effect of water-level changes in the lower sand layer on water-level changes in the Buckeye Mine (Table 4) is also interpreted to reflect a component of recharge that is related to vertical percolation through the intact overburden. Note that the water level in Well 6B actually fell below the level in Well 2A during spring 1991 (Fig. 5), so that the lower sand layer could not possibly be contributing recharge to the mine after that time, although the upper sand, whose level (Well 2B) remained above the mine, still could be contributing in areas where the lower sand is absent.

The independent effect of precipitation on water-level changes in both the Buckeye Mine and Unit G is more difficult to interpret, but it must reflect some component of recharge that effectively bypasses the overburden. Such an effect might arise from lateral percolation from the coalbed's subcrop or direct vertical flow through boreholes or fractures that penetrate the overburden. Regardless of the mechanism, this is the dominant factor in observed water-level changes in both aquifers. In the case of the mine aquifer, the coefficient of precipitation is more than an order of magnitude greater than the coefficient of the lower sand (Table 4), indicating that any vertical percolation through intact interburden must involve a much smaller quantity of water than does lateral percolation or direct vertical flow (whichever is operating). The dominance of precipitation is less in Unit G, which is consistent with its greater isolation.

The statistical effect of changes of atmospheric pressure is also smaller in Unit G than in the mine aquifer, reflecting the lower coalbed's smaller barometric efficiency (about 0.4). We interpret the significant, positive relationship of water levels in Unit G with levels in the Buckeye Mine to indicate the operation of vertical percolation through the intact interburden.

Long-term rise

We interpret the statistically significant, positive intercept in the regression equation for the Buckeye Mine (Table 4) to indirectly reflect the long-term rise of water level that occurred independently of the other controls. The actual long-term change occurred in a step-like pattern and the average rise over the entire time period is greater than the value implied by the regression constant. If we extrapolate the actual average rate of change of the potentiometric level of the mine voids (0.98 cm day^{-1} for the 502 day period of monitoring) into the past, then the level would have been down to the elevation of the abandoned workings of the Buckeye Mine in June 1986; the Graber Mine was active in the area north of the Buckeye Mine at about that time (Hasenmueller, 1986), and abandoned workings of the Buckeye Mine were encountered and dewatered. Thus, the rise of potentiometric level that we observed during our 15 month investigation may represent the latter stages of reestablishment of conditions that existed before the Graber Mine was active. Even if the Graber Mine had not directly dewatered the underlying, unmined coalbed, the dewatering of the Buckeye Mine may have temporarily disrupted normal recharge to that coalbed, so that its long-term rise may also represent a re-establishment of pre-surface-mining conditions.

Effects of near-surface conditions

The statistical results discussed above do not incorporate certain important effects that we infer to exist from some features of our water-level records. For example, consider the rapid, short-term rise (88 cm in 11.8 days) of the water level in the Buckeye Mine that began in late December 1990 (Well 2A, Fig. 5). The rise, which permanently affected water levels, was associated with a series of snowfalls and sudden thaws. The greatest rate of rise (2.1 cm h^{-1}) occurred after the sudden and complete melting of 10 cm of snow cover, when the air temperature rose during a single day from 4.4°C to 15.6°C. Rainstorms that delivered much greater quantities of water to the surface did not produce such dramatic rises. One possible explanation for this unique event might be that the combination of rapidly melting snow through a thawing surface layer at a time of year when soil moisture is maximal yielded an exceptionally large inflow of percolating water to the mine. In contrast, much of the precipitation from many of the large rainstorms may be shed as surface runoff or used to satisfy the storage capacity of unsaturated surficial materials. This points out that monitoring of conditions near the surface, such as ground temperature and soil-moisture content of unsaturated materials, should ultimately be incorporated into models for water-level changes at depth.

CONCLUSIONS

The geologic complexity of Lower Pennsylvanian strata, compounded by the effects of current and recent mining activity, preclude measurement of flows through the numerous hydrologic pathways — man-made as well as natural — that are conceivable in such a setting. Many of the pathways may be highly localized and difficult to detect, and some (such as subsidence fractures in shale) may even be self-healing and transitory. Nevertheless, in our investigation at the Cannelburg site, we were able to acquire an extensive, digital record of simultaneous water-level changes at four different stratigraphic levels at various locations, including voids in two different mines and in overlying and underlying units. Together with on-site precipitation measurements, these data allowed statistical evaluation of existing relationships between water levels in various hydrogeologic units, and, in conjunction with other field measurements, permitted the drawing of inferences regarding preferred recharge flowpaths into the mine voids.

We believe that at least three recharge mechanisms are operating at the study site. Precipitation that somehow bypasses the overburden of the Buckeye Mine has the strongest effect on both the Buckeye Mine and Unit G, but percolation from overlying aquifers also has a statistically significant effect. In the case of Unit G, the effect of precipitation is probably attributable to lateral flow from the coalbed's subcrop, while some vertical flow through an undetected pathway — possibly mine-associated — contributes to recharge of the Buckeye Mine.

As issues of mine subsidence, refuse disposal, and groundwater contamination grow in importance, the need for comprehensive studies of mine aquifers will increase. Refinement of models to explain or predict hydrologic changes within such aquifers will require monitoring of an ever-expanding base of pertinent variables, some of which may not yet be identified, as well as conventional monitoring of the targeted aquifers across increasingly broader stratigraphic and lateral distances. Financial and technical constraints that are commonly associated with drilling and well installation have inhibited such research efforts, so that our knowledge of the response of abandoned mines to natural and manmade stresses is inadequate to resolve many of the regulatory and legal questions that are arising in areas where there has been extensive underground mining.

ACKNOWLEDGMENTS

Edwin J. Hartke (Head of the Environmental Geology Section, IGS) served as a principal investigator on the project. N. K. Bleuer of the IGS provided descriptions of unconsolidated deposits and guidance in the interpretation of gamma-ray logs. Students in the Department of Geological Sciences of Indiana University who assisted in the project include A. M. Ebraheem, Timothy Eckert, and Yvonne Huff. Useful reviews of this manuscript were provided by Tony Fleming and Curt Ault of the IGS and Les Arihood of the US Geological Survey, Indianapolis. Support for the research was provided by the U.S. Office of Surface Mining, Abandoned Mine Lands Program, through the State of Indiana, Department of Natural Resources, Division of Reclamation, as part of an investigation of hydrologic conditions around Cannelburg, Indiana.

REFERENCES

Ashley, G.H., 1899. The coal deposits of Indiana. Annual Rep. No. 23, Indiana Department of Geology and Natural Resources, Indianapolis, IN, 1573 pp.

Bauer, R.A., 1984. Subsidence of Bedrock Above Abandoned Coal Mines in Illinois Produces Few Fractures. Soc. Mining Engineers AIME, Littleton, CO, Preprint 84-400, 8 pp.

Chugh, Y.P., 1990. Identification of possible impact areas susceptible to potential subsidence due to mining within the proposed boundaries of land unsuitable for mining petition. Final Rep. Indiana Department of Natural Resources, Jasonville, IN, 18 pp.

Cocroft, J.E., 1984. Hydrogeochemical study of a mined region in the Carbondale Group (Pennsylvanian), southwestern Indiana. M.A. Thesis, Indiana University, Bloomington, IN, 198 pp.

Freeze, R.A. and Cherry, J.A., 1979. Groundwater. Prentice-Hall, Englewood Cliffs, NJ, 604 pp.

Harper, D., Hartke, E.J. and Olyphant, G.A., 1991. Abandoned underground mines and hydrologic conditions around Cannelburg, Indiana. Indiana, Geol. Surv., Open-file Rep., 89 pp.

Hasenmueller, W.A., 1986. Directory of Coal Producers in Indiana. Indiana Geological Survey, Bloomington, IN, 60 pp.

Hasenmueller, W.A., 1991. Directory of Coal Producers in Indiana. Indiana Geological Survey, Bloomington, IN, 54 pp.

Hutchison, H.C., 1971. Distribution, structure, and mined areas of coals in Daviess County, Indiana. Preliminary Coal Map 15, Indiana Geological Survey, Bloomington, IN.

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

Ostrem, C.W., 1978. Time Series Analysis: Regression Techniques. Sage, London, 85 pp.

Shaver, R.H. et al., 1986. Compendium of Paleozoic rock-unit stratigraphy in Indiana — a revision. Indiana, Geol. Surv., Bull. 59, 203 pp.

Thompson, D.B., 1987. A microcomputer program for interpreting time-lag permeability tests. Ground Water, 25: 212–218.

Wangsness, D.J., Miller, R.L., Bailey, Z.C. and Crawford, C.G., 1981. Hydrology of Area 32, Eastern Region, Interior Coal Province, Indiana. U.S., Geol. Surv., Water-Resour. Invest., Open-File Rep. 81-498, 76 pp.