GROUNDWATER RESPONSE TO LONGWALL MINING, SALINE COUNTY, ILLINOIS, USA

By C.J. Booth, A.M. Curtiss and J.D. Miller

Department of Geology, Northern Illinois University, DeKalb, Illinois, USA.

ABSTRACT

Hydrogeological studies have been conducted over a longwall coal mine in Saline County, Illinois, since the start of mining in 1989. Six panels have been mined, beneath poorly permeable bedrock overlain by glacial deposits. Our studies examined the effects of two panels on the shallow drift, deep drift, and shallow bedrock sandstone; they included potentiometric monitoring in wells and piezometers, and hydraulic tests before and after mining. The sandstone permeabilities were low and did not generally increase due to subsidence, even where the sandstone was at the bedrock surface, but there were local permeability increases related to discrete bedrock fracturing.

At panel 1 (122 m deep, mined 1989-90), the sandstone is 54 m deep and confined by thick shale under drift. Its water levels dropped rapidly 20-30 m with mining and subsidence, and have not recovered. Over panel 5 (91 m deep, mined 1992-93), the sandstone is 20 m deep and locally in contact with the drift. Its water levels dropped about 18 m with mining and subsidence in the panel's central area, but only about 5 m on the barrier pillar. Water levels declined slightly (even briefly increased) in the till-dominated deep drift in the panel center, but dropped considerably in the more permeable drift on the edge. Although there has been little bedrock recovery, recharge from the drift has apparently cushioned the bedrock head drop at the panel's edge.

The overall potentiometric behavior was consistent with expected models of the groundwater impact of longwall mining, but the results demonstrated that geological variations even at the site scale exercise significant control. In particular, the bedrock aquifer response depends greatly on available geologic pathways for recharge after mining.

INTRODUCTION

Hydrogeological studies have been conducted over an active longwall coal mine in Saline County, south-eastern Illinois, initially as part of the Illinois Mine Subsidence Research Program (IMSRP) and currently with support from the Office of Surface Mining (OSMRE) of the US Department of the Interior. These studies have been conducted jointly with the Illinois State Geological Survey (ISGS). The first phase of the study was in 1989-91 during and after the mining of panel 1 (depth 122 m). Some early results of this phase have been reported [1, 2, 3, 4, 5]. The second phase is an ongoing investigation (since 1992) of panel 5, which was mined at a depth of about 91 m. This paper reviews and updates the panel 1 results, and is the first publication of hydrogeological results of the panel 5 phase.

Our primary interest was in the effects of mining and subsidence on the groundwater behavior in the overlying aquifers, not on inflow to the mine. Longwall subsidence is accompanied by fracturing and

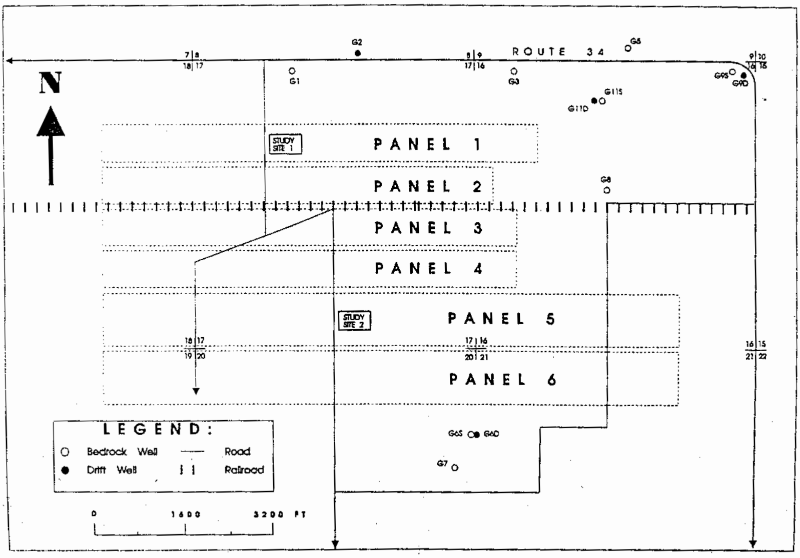

Figure 1. Map of Saline County Study Site, Showing Longwall Panels.

bedding separations, which can change the hydraulic properties of overlying strata and, therefore, their groundwater flow and potentiometric heads. These changes occur regardless of any inflow to the mine. From previous studies [e.g. 6, 7, 8], there is typically a sharp localized decline in bedrock potentiometric levels in the active subsiding zone, attributed to increased void space and drainage of water to other levels. This zone is surrounded by an expanding "cone of depression" of declining heads; all these zones advance with the mine face. Potentiometric recovery after mining may result from partial recompression of void space and recharge into the aquifer.

Our previous studies at this and another site in Illinois have suggested [1, 2, 8] that the recovery, and hence the ultimate impact of longwall mining on aquifers, depends on geological continuity with recharge sources. Over this mine, the geology varies such that the bedrock sandstone aquifer is shallower and in better contact with the drift over panel 5 than over panel 1. We had hypothesized that the sandstone over panel 5 would therefore have more open subsidence-induced fracturing and would recover more quickly from mining. As this paper shows, the effects have been more complex and more dependent on very local conditions than anticipated.

Site Description

The area is gently rolling farmland with local relief less than 15 m. This section of the mine consists of six longwall panels, each mined back from east to west distances of 2 to 3 km (Figure 1). Panel 1, in the north, was mined in 1989-90, panel 5 in 1992-93, and panel 6 in 1994. The mined No. 6 (Herrin) Coal is up to 2 m thick; longwall mining produces rapid subsidence of up to 1.5 m. The subsidence is accompanied by tension cracks at the surface and intense fracturing above the mine, but ISGS studies have shown that the bulk of the overburden here has little major fracturing and subsides more or less coherently.

The bedrock (all Pennsylvanian) over the mined coal is mainly shales, siltstones, and claystones, with minor sandstone and limestone units (Figure 2). The bedrock surface is 18 - 30 m below ground, and is overlain by glacial drift, consisting mainly of till but including minor sand-and-gravel units, glacial lake deposits, and a loess cover. The site is on the northern flank of a minor anticline, so that the bedrock strata rise gently southward. The Trivoli Sandstone is at the bedrock surface at a depth of about 20 m at panel 5 in the south, but 54 m deep and covered by 37 m of shale at panel 1 in the north.

Our investigation has focused on responses to longwall mining in three zones: the shallow drift, the lower drift, and the upper bedrock sandstones. The few local farm and residential wells are either large-diameter wells into the shallow drift or drilled wells into one of the shallow sandstones. We have monitored water levels in these and in several piezometers drilled over and near panels 1 and 5, and have conducted slug and pump tests in piezometers and packer tests in cored pre- and post-subsidence boreholes over both of the study panels.

Investigations at Panel 1

Panel 1 (mined May 1989 - March 1990) was 204 m wide and 2400 m long, and about 122 m deep. The ISGS installed and monitored [3, 4, 5] piezometers into the lower drift aquifer at depths of 18-23 m, and into bedrock sandstones at depths of around 50-60 m. These were undermined in late 1989.

Results of bedrock hydraulic tests over panel 1 are summarized in Table I (values are rounded off for clarity). Slug tests in sandstone piezometers indicated low permeabilities (10^{-5} cm/s) both before and after subsidence. Packer tests were conducted in cored boreholes GT1 (pre-subsidence, 130 m deep) and GT2 (post-subsidence, 84 m deep) at the panel centerline. Before mining, most of the bedrock was too poorly permeable for water intake, but the Trivoli Sandstone (here 54 m deep and 8 m thick) briefly accepted water, with a permeability calculated at about 6×10^{-8} cm/s. This remained about the same after subsidence, but the water intake became sustainable, suggesting that the fractures had become more extensive and continuous. Several zones beneath the sandstone developed minor permeability (10^{-7} to 10^{-8} cm/s).

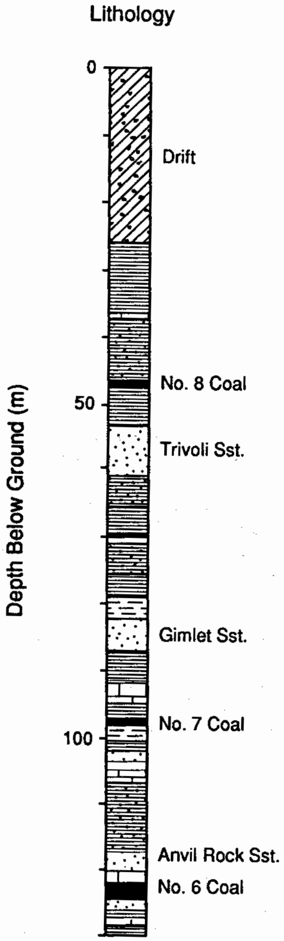

Figure 2. Site Stratigraphy.

TABLE I. HYDRAULIC TEST RESULTS IN THE SANDSTONE AQUIFER OVER PANEL 1

Piezometer		Hydraulic Conductivity (cm/s)	
No.	Location	Pre-Subsidence	Post-Subsidence
P1W well	centerline	3x - 4x 10^{-5} (pump)	N/A
GT1/GT2	centerline packer tests	6x 10^{-6} localized	5x 10^{-6} extensive
BP3/BPPS	central panel	3x 10^{-5}	3x 10^{-5}
BP4	centerline	4x - 5x 10^{-5}	N/A
BP6	outer panel	5x 10^{-5}	N/A
BP7	barrier pillar	2x 10^{-5}	4x 10^{-5}
		after panel 2:	6x 10^{-5}

Piezometers were also screened into the deep drift at depths of 17 to 23 m. Slug tests (after mining) indicated permeabilities in the range 3×10^{-4} to 2×10^{-3} cm/s. Premining potentiometric levels in the deep drift were around 7 m below ground level. The levels in the piezometers over the panel, but not off-panel, responded noticeably to mining (Figure 3). They rose slightly when the mine was about 300 m away, then fell sharply 2-3 m when the site entered the subsidence tensional phase. After rapid fluctuations in the compressional phase, the deep drift potentiometric levels have fluctuated between about 8 and 11 m below ground.

The bedrock potentiometric levels over the panel center declined about 22 m just ahead of mining and a further 8 m as the site subsided. Except for a brief rise during the compressional phase, they have not recovered; the residual post-mining depression (to 1993) is about 30 m. Off-panel well G2, into an upper bedrock sandstone 300 m to the north, had an earlier response (Figure 4); its water level began to drop when the mine face was still 1 km away, and ultimately declined by about 20 m. It showed no recovery until a very small (1 m) rise in late 1993. In contrast, the water table observed in several shallow drift wells about 300 m north of the panel did not respond to mining.

INVESTIGATIONS AT PANEL 5

Panel 5 (Figure 1) was mined from July 1992 to May 1993, 3092 m east to west with a face width of 282 m, at a depth of around 91 m. Prior to mining, a cored borehole (GT3), a piezometer/test well (P5W), and twelve other piezometers were drilled on a transverse line across and south of the panel. Piezometer clusters, mostly with bedrock (B), deep drift (D), and shallow drift (S) piezometers, were located as follows: P51 (central area 100 m north of the southern edge of the panel), P52 (inner zone 46 m north), P53 (outer tension zone 12 m north), P54 (21 m south on the barrier to next panel 6), and P5C (off panel 244 m south). The instrumented site was undermined at the beginning of January, 1993. The only piezometer to suffer significant damage was P51B (bedrock piezometer in the central area), which was replaced by piezometer P51BR.

At the center-zone piezometer site, the top of the bedrock is 18-20 m below ground and consists of 0-2 m of shale overlying the Trivoli Sandstone, which is up to 4 m thick. To the south (panel edge and barrier pillar) the Trivoli subcrops in contact with the drift, while farther south at the control site it is locally missing by erosion.

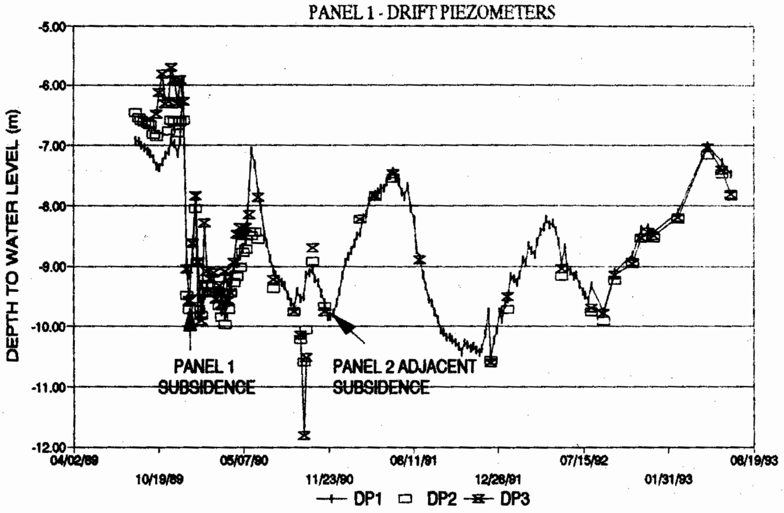

Figure 3. Hydrographs of Drift Piezometric Levels at Panel 1.

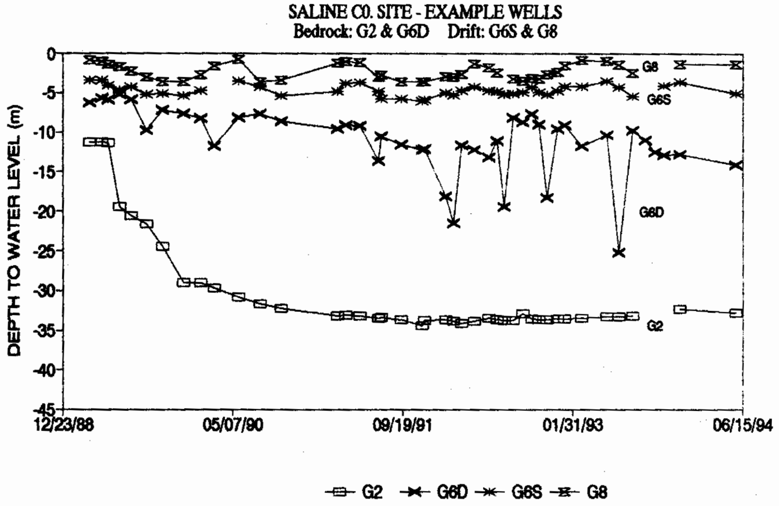

Figure 4. Hydrographs of Selected Well Water Levels.

Hydraulic Tests Over Panel 5

Packer tests were conducted over the central area of panel 5 in borehole GT3 before subsidence (June 1992) and in borehole GT4 afterwards (June, 1993). Hydraulic conductivity was calculated using the Hvorslev formula [9] which is well established for packer test analysis [e.g. 10].

Pre-Subsidence Packer Testing: GT3 Borehole GT3 was cored from the top of the bedrock (19 m) to a total depth of 61 m. The cores were tight with no open fractures. Packer tests were conducted with 6-m injection intervals throughout the bedrock, most of which was too tight to accept water. The only measurable water take was in the 21-27 m interval covering the Trivoli Sandstone, which had a hydraulic conductivity of around $4x10^{-6}$ cm/s. Staggered testing showed that the top part of the sandstone was the only significantly permeable zone.

Post-Subsidence Packer Testing: GT4 GT4 was cored and tested seven months after subsidence. Although this hole was only 5.2 m from GT3, the bedrock surface was almost 2 m lower and the top of the Trivoli Sandstone, its most permeable zone, was missing. The hole was continued through shale and limestone to a total depth of 40 m, when drilling problems prevented further progress. Discrete fractures or bed separations were indicated at 32.3 and 32.9 m.

Only two intervals had measurable intake. The most permeable was in the fractured 32-38 m interval below the Trivoli Sandstone. The apparent hydraulic conductivity was about $4.5x10^{-5}$ cm/s, although the true value for just one or two fractures would be higher. The other intake was in the 23-29 m interval covering the accessible Trivoli Sandstone and underlying shale. The erratic step results in this interval suggested injection was into discrete cracks of limited volume; the permeability values, which ranged from 1.6x - $4.3x10^{-6}$ cm/s, were probably highly localized.

Other Hydraulic Tests Tables II and III summarize the bedrock and drift hydraulic test results over panel 5. The results of a pre-mining pump test, conducted in the Trivoli Sandstone well P5W over the inner panel, were analyzed for the test well and for observations in P51B and P52B by standard Theis-based methods. Slug tests were conducted before, after, and in some cases during subsidence in most of the piezometers; their results were analyzed by standard methods [11, 12].

TABLE II. HYDRAULIC TEST RESULTS IN THE SANDSTONE OVER PANEL 5

Piezometer			Hydraulic Conductivity (cm/s)	
No.	Location	Pre-Subsidence	During Subs.	Post-Subsidence
P5W	Central	$3x 10^{-5}$ (pump)		$7x 10^{-5}$ (slug)
P51B/P51BR	Central	$2x 10^{-4}$ (pump) 1x - $4x 10^{-6}$	2x - $7x 10^{-4}$	$8x 10^{-7}$ (slug)
GT3/GT4	Central	3x - $4x10^{-6}$ (packer)		1x - $5x 10^{-6}$
P52B	Inner	$4x 10^{-4}$ (pump) $3x 10^{-6}$ (slug)		5x - $7x 10^{-5}$
P53B	Tension	$4x 10^{-7}$	5x - $8x 10^{-7}$	$2x 10^{-7}$ (slug)
P54B	Barrier	2x - $5x 10^{-6}$	$1.0x 10^{-6}$	$1x 10^{-6}$ (slug)

As has been observed earlier [8], the values obtained by different methods (pumping, slug, packer) can be substantially different, due to such factors as scale effects, extent and intervals of aquifer tested, and non-applicability of the analytical models to the non-ideal aquifer. However, the slug and packer tests agree well, and indicate permeabilities in the Trivoli Sandstone in the central area in the range 10^{-7} to 10^{-6} cm/s, similar to values obtained over panel 1. The pump test results were one to two orders higher. The permeabilities increased briefly during subsidence in P51B, but then declined back. There is no indication of permanently increased permeability except in P52B, which may have experienced some residual tension.

Permeabilities in the deep drift vary considerably across the site, reflecting local variations in lithology. The sand-and-gravel unit is thicker on the southern edge and barrier pillar of the panel than in the central zone. Thus, the inner piezometers, screened mainly in till, have considerably lower conductivities than the outer. There was little to no change in drift permeability values due to subsidence.

TABLE III: SLUG TESTS IN THE DRIFT OVER PANEL 5

Piezometer		Hydraulic Conductivity (cm/s)		
No.	Location	Pre-Subsidence	During Subs.	Post-Subsidence
Deep Drift:				
P51D	Central	$8x10^{-8}$ - $3x10^{-7}$		$1x\ 10^{-7}$
P52D	Edge	1x - $2x\ 10^{-6}$		1x - $7x\ 10^{-6}$
P53D	Edge	$2x\ 10^{-6}$	$6x\ 10^{-7}$	$9x10^{-7}$ - $2x10^{-6}$
P54D	Barrier	$6x10^{-5}$ - $2x10^{-4}$		
P5CD	244 m S.	$1x\ 10^{-4}$		
Shallow Drift:				
P51S	Central	1x - $3x\ 10^{-5}$		$3\ x10^{-5}$
P54S	Barrier	3x - $4x\ 10^{-4}$		N/A

Potentiometric Response

Drift Aquifer. The potentiometric responses in the drift (Figure 5) varied considerably across the site. The first response was in late November 1992, when the mine face was about 300 m away; by mid-December the deep drift water levels, initially 2-3 m deep, had fallen by as much as 11 m. Shallow drift water levels did not respond until the mine was less than 60 m away. The water level minima in the drift piezometers occurred during the subsidence tension phase, about two to four days before and 15-30 m ahead of undermining.

Despite the overall declining trend, the heads in inner piezometers P51S, P51D, and P52D briefly rose and water flowed out of the pipes when the site was directly undermined. Subsequently, water levels declined again. In outer piezometers P53D and P54D, water levels declined and have remained significantly depressed at about 10 and 6 m below pre-mining levels, while central piezometer P51D has only a slight (2 m) residual depression. Shallow P51S has a residually higher water level reflecting the local ground subsidence. No response occurred in off-panel P5CD.

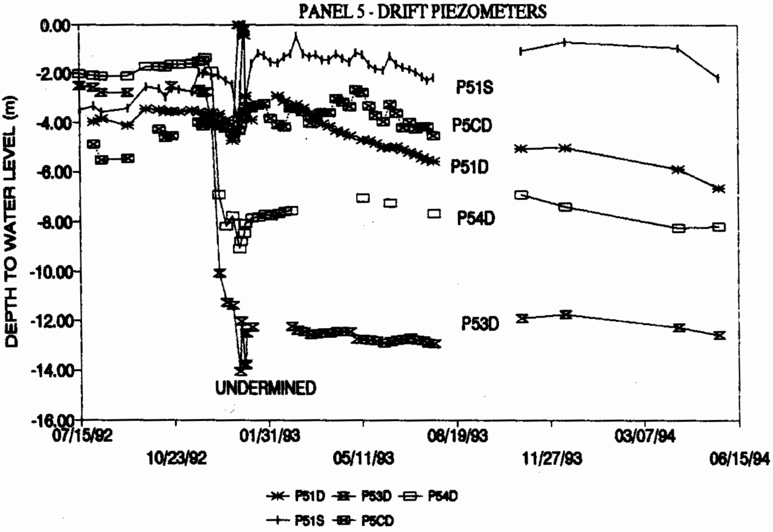

Figure 5. Hydrographs of Drift Piezometric Levels at Panel 5.

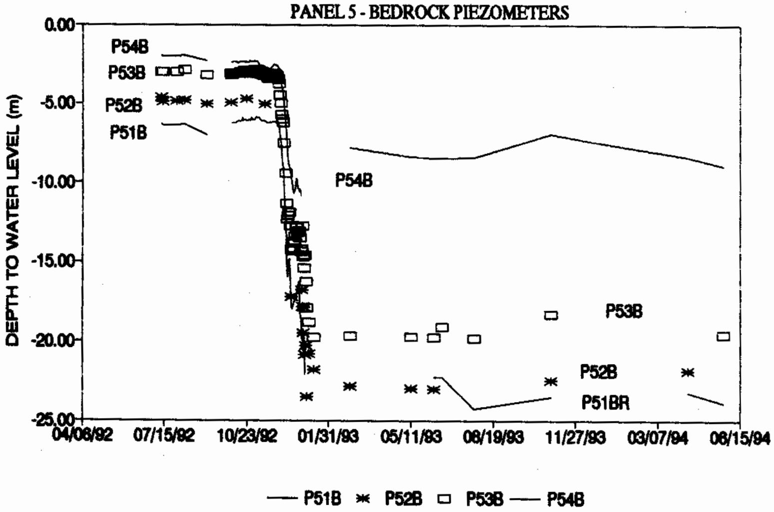

Figure 6. Hydrographs of Bedrock Piezometric Levels at Panel 5.

Bedrock. Bedrock piezometers P51B, P52B, P53B and P54B, located progressively southward from the center zone to the barrier pillar, are screened in the Trivoli Sst at depths from 19 to 24 m. Prior to mining of panel 5, the potentiometric surface across the site was almost horizontal; the slight pre-mining water-level depth differences (Figure 6) reflected local topographic variations. The first bedrock response to mining was in November 1992 when the mine was about 490 m away. By mid-December, when the mine was about 120 m away, the water levels over the panel had dropped to around 18 m deep, just above the top of the sandstone. The subsidence tensional phase began on January 2, 1993, indicated by surface fractures, the shearing of P51B, and the near dewatering of P52B and P53B.

The sandstone potentiometric levels in P51BR, P52B, and P53B over the panel have remained up to 18 m depressed in the eighteen months since undermining, though slight rises occurred during the recent winter. Mining of adjacent panel 6 may have delayed recovery. However, the barrier piezometer P54B (nearest to panel 6) has maintained a higher water level both in absolute elevation and in shallowness (by about 14 m), probably because of recharge from the drift. Clearly, there is a major potentiometric depression over panel 5.

No direct potentiometric effect was observed at the nearest residential bedrock well, G6D into the Trivoli some 427 m south of panel 5 and 180 m south of panel 6. The hydrograph (Figure 4) shows brief potentiometric lows due to occasional intensive pumping, superimposed on a gradual decline in static water level from 6 m deep in 1989 to 13 m in summer 1993, as successively closer panels were mined. When panel 6 was 700 m away, the pumping level in G6D fell to 25 m, well usage was terminated, and alternative supplies were provided. The static water level then rose to about 9 m deep, before declining to 14 m in 1994.

CONCLUSIONS

Permeability Changes

Tests at both panels revealed a very tight bedrock in which the principal sandstone "aquifer" has an average hydraulic conductivity of the order 10^{-6} cm/s. Contrary to expectations, there was little increase in permeability in the sandstone due to subsidence, even at the southern panel where, because of the sandstone's position at the bedrock surface, more fracturing had been predicted. Permeability increases were either brief (during the tensional phase) or localized (probably in zones of residual tension). The greatest increases were associated with discrete fracturing or bedding separation, but not necessarily in the sandstone.

Potentiometric Response

Potentiometric levels in the sandstone over both panels declined sharply more than 20 m with the approach of the mine and with subsidence. Except for brief potentiometric rises during the compressional phase, no significant recovery has occurred in the bedrock over the panels themselves in the four years since panel 1 and the eighteen months since panel 5. However, slight rises at panel 5 in the recent winter may presage some recovery. Off-panel responses varied. An upper sandstone well (G2) downdip from panel 1 had an early, major head drop with no significant recovery, whereas a Trivoli Sandstone well (G6D) south of panels 5 and 6 displayed a gradual decline in potentiometric level as successively closer panels were mined.

The thick, tight confining layers precluded drainage from the shallow sandstones to the mine or to lower units. The head drops appear to be an in-situ result of the increase in fracture and bedding plane void space during subsidence. This creates a local potentiometric low which induces a hydraulic gradient (and head loss) in the surrounding area. The spatial and temporal steepness of the gradient, and hence the nature of the head drop, depend on the unit's permeability - the response is later and more localized in less transmissive units.

The potentiometric recovery depends on recharge to the affected zone, either laterally or from overlying units. The sandstones at panel 1, poorly permeable, overlain by shales, and blocked updip by continued mining, have received no recharge and experienced no recovery. The permeable deep drift over panel 1, separated from the bedrock by thick confining units, did not drain to (recharge) the bedrock, and experienced only slight head drop.

The response and recovery at panel 5 was spatially variable and appears to be controlled by the deep drift aquifer. Over the central area, the deep drift is mainly poorly permeable till, but it had only slight declines in head, preceded during active subsidence by transient rises. The more permeable sand-and-gravel drift at the edge of panel 5 had the greater head drop and lower residual water level, whereas the bedrock potentiometric levels declined much more in the center than on the edge. The head difference between the deep drift and bedrock is 18 m in the center but less than 1 m on the barrier; clearly, the sandstone is in good continuity with the permeable drift at the panel edge and is receiving recharge from it.

The results were consistent with the general model of potentiometric response suggested by studies at other longwall mines, but they do indicate that any individual set of observations or predictions must be considered in the context of geological variations at the most local level. In particular, the potential geological pathways for recharge at site scale critically control the initial response and eventual recovery of the bedrock water levels.

ACKNOWLEDGEMENTS

We acknowledge the support of the Illinois Department of Energy and Natural Resources (DENR) through an IMSRP grant, for the early phase of this study, and of the US Department of the Interior, Office of Surface Mining Reclamation and Enforcement (OSMRE), through agreement GR196171, for the current phase. This support does not constitute an endorsement by either DENR or OSMRE of any views expressed in this article, which are solely those of the authors.

We also thank Brenda Mehnert, Dan Van Roosendaal, Philip DeMaris, and Robert Bauer of the ISGS for provision of data and for their cooperation in this joint project.

REFERENCES

1. Booth, C. J. and E. D. Spande, 1991. Changes in Hydraulic Properties of Strata over Active Longwall Mining, Illinois, USA. Proc. 4th International Mine Water Congress, Portschach, Austria/Lubljana, Slovenia, September, 1991, pp. 163-174.

2. Booth, Colin J., 1992. Hydrogeologic Impacts of Underground (Longwall) Mining in the Illinois Basin. Proc. 3rd Subsidence Workshop Due to Underground Mining, Morgantown, WV, June 3, 1992: p. 222-227

3. Mehnert, B. B., D. J. Van Roosendaal, R. A. Bauer, and D. F. Brutcher. Effects of Longwall Mine Subsidence on Overburden Fracturing and Hydrology in Illinois, 1990. Proc. Mine Subsidence-Prediction and Control Symp., Assoc. Engineering Geologists, 33rd Ann. Meeting, Pittsburgh, Oct. 1990, p. 105-112.

4. Van Roosendaal, D. J., D. F. Brutcher, B. B. Mehnert, J. T. Kelleher, and R. A. Bauer, 1990. Overburden Deformation and Hydrologic Changes Due to Longwall Mine Subsidence in Illinois. Proc. Third Conf. on Ground Control Problems in the Illinois Coal Basin (Y. P. Chugh, ed.), SIU-Carbondale, Aug. 1990, p. 73-82.

5. Kelleher, J. T., D. J. Van Roosendaal, B. B. Mehnert, D. F. Brutcher and R. A. Bauer, 1991. Overburden Deformation and Hydrologic Changes Due to Longwall Coal Mine Subsidence in the Illinois Basin. In:IAHS Publ. 200: Land Subsidence, Proc. Fourth International Symp. on Land Subsidence, Houston, May 1991, p. 195-204.

6. Hill, J. G. and D. R. Price. The Impact of Deep Mining on an Overlying Aquifer in Western Pennsylvania. Ground Water Monitoring Review, v. 3, 1983, no. 1, p. 138-143.

7. Matetic, R. J. and M. A. Trevits. Case Study of Longwall Mining Effects on Water Wells. Preprint No. 90-141, SME Annual Meeting, Salt Lake City, UT, Feb 26-Mar 1 1990, 7 p.

8. Booth, C. J. and E. D. Spande, 1992. Potentiometric and Aquifer Property Changes Above Subsiding Longwall Mine Panels, Illinois Basin Coalfield: Ground Water, v. 30, no. 3, pp. 362-368.

9. Hvorslev, M.J., 1951. Time Lag and Soil Permeability in Groundwater Observations. Bulletin 36, Waterways Experiment Station Corps of Engineers, US Army, Vicksburg, Mississippi, 49 pp.

10. US Department of the Interior, 1981. Ground Water Manual: A Water Resources Technical Publication. (Revised edition). US Department of the Interior, Water and Power Resources Service. John Wiley, New York, 480 p.

11. Bouwer, H. and R. C. Rice, 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resources Research, v. 12, no. 3, p. 423-428.

12. Cooper, H.H., J.D. Bredehoeft, and I.S. Papadopulos, 1967. Response of a Finite Diameter Well to an Instantaneous Charge of Water. Water Resources Research, vol. 3, pp. 263-269.