Positive and negative impacts of longwall mine subsidence on a sandstone aquifer

C. J. Booth · E. D. Spande · C. T. Pattee · J. D. Miller · L. P. Bertsch

Abstract Subsidence due to longwall underground coal mining changes the hydraulic properties, heads, yields, and in some cases the groundwater chemistry of overlying bedrock aquifers. A 7-year study of a sandstone aquifer overlying an active longwall mine in Illinois has supported a comprehensive model of these impacts. Subsidence caused increases in permeability and storativity over the longwall panel. These changes initially caused a major decline in water levels in the sandstone, but the aquifer recovered slightly within a few months and fully within several years after mining. The enhanced hydraulic properties combined with potentiometric recovery resulted in a zone of greater well yield. However, at sites with very poor transmissivity and inadequate recharge pathways, recovery may not occur. Also, at the study site, the physical enhancement was accompanied by a deterioration in groundwater quality from slightly brackish, sodium bicarbonate water to more brackish water with increased sulfate levels.

Key words Aquifer properties · Mining · Subsidence

Introduction

Longwall mining is a preferred method of underground coal extraction because of its safety, efficiency, and high extraction rate. However, it invariably produces rapid ground and strata subsidence, which affect overlying aquifers. The most common concern is the loss of well water levels, but the total hydrogeological impact also involves complex changes in heads and hydraulic properties, affecting well yields, groundwater flow, and groundwater chemistry.

This paper discusses the impact of longwall mining on overlying bedrock aquifers, and describes a long-term, comprehensive hydrogeological study of such an impact on a minor sandstone aquifer in the Illinois Basin coalfield, USA. In this region, groundwater resources are generally poor but locally important for agricultural and residential use. Whereas traditional room-and-pillar mining has had little effect on aquifers, longwall mining can have noticeable effects because of subsidence. Any impacts (positive or negative) on the marginally usable aquifers in this setting could be significant not only for current usage but also for potential utilization of the aquifers as reserve water supplies in the event of drought.

This study began in 1988 as part of the state-supported Illinois Mine Subsidence Research Program (IMSRP) and continued with support from the US Office of Surface Mining (OSM) until 1995. It was conducted cooperatively with the Illinois State Geological Survey (ISGS) which also carried out concurrent subsidence monitoring and geotechnical studies. Selected results have been reported by various members of the research group in conference papers (for example: Mehnert and others 1990; Van Roosendaal and others 1990; Kelleher and others 1991), abstracts (Pattee and Booth 1992; Booth 1995, 1996), contract reports (Mehnert and others 1994; Trent and others 1996), and Northern Illinois University graduate theses (Spande 1990; Pattee 1994; Miller 1996; L.P. Bertsch, in preparation). The early (1988–1990) hydrogeological work was reported by Booth and Spande (1992). Parts of this material are summarized in this paper because they are essential aspects of the total long-term aquifer impact described here.

Effects of longwall mining

Longwall mining achieves a high percentage of coal recovery because it does not leave substantial reserves behind as pillars to support the mine roof. Instead, large rectangular areas (panels) of coal are completely extracted in a process in which the roof over the working coal face area is temporarily supported by movable shields. The shields advance as the face advances, and behind them the roof collapses almost immediately into the

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mined-out area. This subsidence works its way up through the overlying strata to the ground surface, where it produces a trough-like depression that outlines the growing mined-out panel. During subsidence, the strata undergo fracturing, opening of joints, and separation of bedding planes, that cause general increases in fracture permeability and porosity. These changes in hydraulic properties cause changes in hydraulic heads, gradients, and other features of groundwater flow.

Permeability changes due to subsidence have been reported in a few studies (e.g., Aston and Singh 1983; Matetic and Trevits 1992). Hydrologic responses have been reported from several case-studies in the Appalachian coalfield (e.g., Hill and Price 1983; Moebs and Barton 1985; Schulz 1988; Tieman and Rauch 1987; Dixon and Rauch 1988; Walker 1988; Johnson 1992). In these studies, groundwater levels typically declined with subsidence, due to the increased fracture porosity, but often recovered after months or years. However, permeability changes can also lead to permanent effects such as altered hydraulic gradients, depressed water levels, leakage between units, and changes in spring discharge. In flat terrains, subsidence has also caused problems due to high water tables (Kratzsch 1986). In Illinois, the only study of the hydrogeological effects of longwall mining prior to IMSRP was by Pauvlik and Esling (1987), who observed water-level fluctuations in a glacial till aquitard.

It is generally accepted that the effects of subsidence are primarily internal responses to hydraulic property changes within the aquifer, not the result of drainage to the mine. The lowest zone of the overburden strata undoubtedly experiences severe fracturing and loses water directly into the mine workings. Nevertheless, the overburden typically includes a thick intermediate zone which subsides more coherently, maintains overall confining (aquitard) characteristics, and hydraulically separates any shallow aquifers from the mine inflow region.

The subsidence-related deformation has a systematic, predictable spatial and temporal pattern. Subsidence at the ground surface closely follows the position of the advancing mine face. The forward part of the subsiding zone, and thus the earliest phase of subsidence, is tensional; the rear part, and thus the later phase, is compressional. The tension-compression pattern is observed at the ground surface as aligned surface cracks, which appear, widen, and then close back up; this is expressed in the subsurface as initial dilation and later compression of joints and bedding-planes. The sequence of tension and compression is reflected in zones across the subsidence trough. The outer margins (sides and ends) of the trough experience only the tensional phase, whereas the inner area of the trough is swept by both the tensional and later compressional phases.

The hydraulic effects of these deformations are somewhat predictable. The dilation-compression sequence results in changes in pore-water pressure, manifested as first a decrease and then an increase in head. Increases in permeability and storage coefficient occur over the entire subsided area, although there will be considerable variations depending on the local rock characteristics such as initial jointing and tendency to fracture. In particular, consolidated bedrock is hydraulically much more responsive to fracturing than unconsolidated materials with high primary porosity. Spatially, the maximum residual increase in permeability should be located on the unrelaxed tensional margins. However, the entire rectangular subsidence trough overlying the panel may ultimately become an enhanced aquifer zone of increased permeability, storage, and well yield.

Description of the Jefferson County site

The study site is located in Jefferson County in south-central Illinois, USA, a rural area of arable farming, pasture, and patchy woodland. The gently rolling landscape has about 15 m of local relief. The climate is continental, with an annual rainfall of about 100 cm. Surface water drains in small streams to a large artificial lake east of the site.

Geology

The site is underlain by Pennsylvanian bedrock capped by 3–10 m glacial till, minor sand-and-gravel units, and loess. The bedrock strata are relatively undeformed, flat-lying, and dip regionally 2–3 m/km to the east-northeast. The study panels were positioned to avoid an inactive normal fault zone which trends north-northwest just to the east. The fault dips west and does not intersect the bedrock over the mine. At the study site, the mined Herrin Coal is about 3 m thick at a depth of 220 m. The overlying bedrock strata (Fig.1, which shows both older and newer stratigraphic terminology) are typical of the Pennsylvanian coal measures of the Illinois Basin: predominantly shales and siltstones with minor limestones, sandstones, and coals. However, about 174 m above the seam is the Mt Carmel Sandstone, a minor aquifer about 24 m thick. Above this is a shale, variably up to 18 m thick with an eroded, weathered top, overlain by the glacial deposits.

Mining

This study area of the mine consists of four longwall panels mined between 1987 and 1989. The panels were approximately 183 m wide, separated by 61-m-wide double-pillar barriers, and were mined east to west a distance over 1.5 km. The ISGS monitored the subsidence over panels 3 and 4 (Mehnert and others 1994). Panel 4 began mining in late November 1988, and undermined the instrumentation (located about 850 m from the start line) in February 1989. Ground subsidence started less than 30 m behind the face position, and vertical displacement reached 2 m within 6 weeks of undermining and 2.1 m at the centerline after 3 years. The barrier between panels 3 and 4 subsided 0.44 m. Maximum surface tensile and

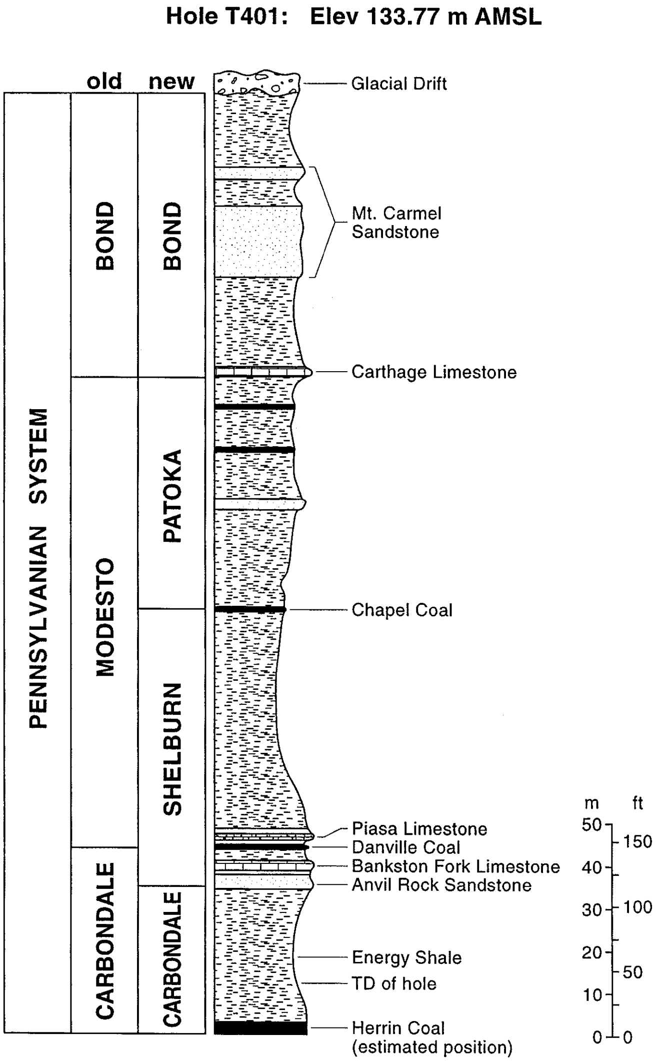

Fig. 1
Stratigraphic column of the Jefferson County site

compressive strains occurred, respectively, 22 and 60 m inside the edge of the panel. Geotechnical studies in boreholes over the panel showed that failure progressed upwards over time through the overburden (Mehnert and others 1994). Over the edge of the panel, deformation occurred mainly as shear in weaker beds or on strong-weak interfaces. Over the center, failure occurred mainly as bedding separations, especially at lithologic interfaces.

Hydrogeology

The shallow hydrogeological units at the Jefferson County site are the surficial drift aquifer, the upper confining shale, and the Mt Carmel Sandstone aquifer. This paper focuses on the sandstone. The thick underlying sequence is dominated by poorly permeable strata and can be considered a confining unit between the sandstone aquifer and the mine.

The surficial drift aquifer is tapped by large-diameter shallow wells, in which the water table was typically less than 3 m deep. Water in the drift was fresh and mainly of sodium-calcium-sulfate type; its main quality problem is high nitrate levels. The groundwater chemistry of the drift was not affected by mining. The water-level depths in drift wells were also largely unaffected by subsidence, except that minimum water levels in certain drift wells located on barrier pillar areas became lower, probably in response to the lower water-table elevations in adjacent subsidence troughs (Pattee 1994).

The upper confining shale contains a few wells, mainly into the weathered zone at its top. The water levels were lower than the water table in the drift but higher than the heads in the underlying sandstone. The shale water was brackish (1000–4000 mg/l TDS) and of mixed-cation sulfate type. Even this poor water is used locally for residential and farm purposes. The hydrochemistry of some wells indicated occasional recharge by fresher water from the drift, especially after mining. Water levels in the shale directly over and adjacent to the longwall panels were substantially lowered by mining, dewatering some wells. Recovery took from months to 3 years. The effects on shale wells about 200 m from panel 4 were negligible.

The Mt Carmel Sandstone is used as a water source in the general vicinity, though not over the mine site itself. At the study site, the sandstone is about 23 m deep and the whole aquifer is about 24 m thick, divided into upper and lower benches (3–5 and 12–16 m thick) by a shaley siltstone unit up to 6 m thick. The benches combine farther east but, as this study demonstrated, are hydraulically separate at the site. The site appears to be in the channel facies of the sandstone, on a western bend of the paleochannel, the nearest edges of which are located about 1.6 km to the west and 2.4 km to the north. The following discussion addresses the hydraulic properties, potentiometric levels, and groundwater chemistry of the sandstone aquifer.

Instrumentation and hydraulic testing of the Mt Carmel sandstone

In 1988, the ISGS drilled several piezometers into the sandstone: two over panel 3, three (P302, P303, P304) over and one (P306) north of panel 4, and a test well (P350) at the center of panel 4 on the transverse piezometer line (Fig. 2). The test well was a 15-cm-diameter hole open 25 m through the full thickness of the sandstone, to a depth of 47 m. The piezometers were constructed with 2.54-cm-diameter PVC pipes and 3-m-long screens, and were instrumented with pressure transducers and automatic recorders.

The ISGS started potentiometric monitoring during the mining of panel 3 and continued until the piezometers over panel 4 were damaged by subsidence (Mehnert and others 1994). The test well (P350) remained usable, and two new piezometers (P410 and P411) were drilled into

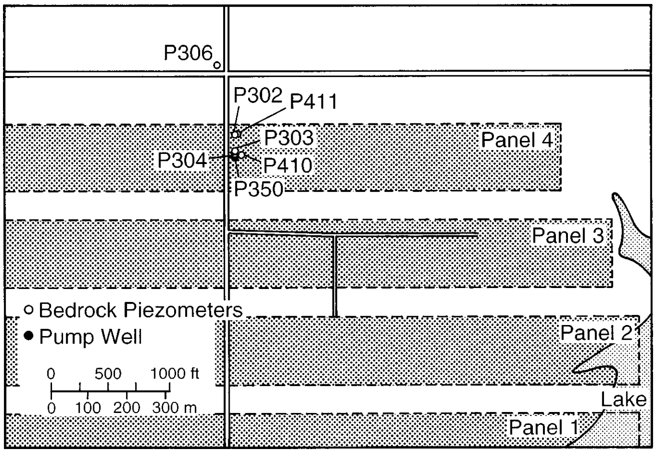

Fig. 2
Map of Jefferson County site showing locations of piezometers and longwall panels

the sandstone in the central and tension-margin zones of the subsidence trough in 1991. Monitoring over panel 4 was thus continued, by recording transducer or manual drop line, until 1995, 6 years after undermining. Construction details for all panel 4 sandstone boreholes are given in Table 1.

The piezometers were used for permeability slug testing and for drawdown observations during pumping tests of well P350. Additionally, two boreholes were drilled over the panel 4 centerline before (T401) and after (T402) mining, and packer-permeability tested.

Slug tests

Slug tests were conducted in piezometers P302-P304 before subsidence (Spande 1990) and in P410-P411 afterwards (Pattee 1994). Because the narrowness of the piezometer pipes prevented insertion of solid displacement slugs, falling-head tests were conducted by the rapid introduction of a small quantity of water into the hole. The head responses were monitored on the recording transducers, and analyzed for hydraulic conductivity using the method of Bouwer and Rice (1976) modified by Bouwer (1989). Inaccuracies introduced by the noninstantaneous injection of the water were significant for the post-subsidence piezometers P410 and P411, in which open fractures (evident during drilling) probably produced hidden water losses during the injection, causing underestimates of the conductivities.

Packer tests

Pre- and post-subsidence straddle packer tests were conducted on the centerline of panel 4 in 7.6-cm-diameter boreholes, core-drilled at angles of 10° off vertical to intercept fractures. Following standard procedures (US Department of Interior 1981), water was injected into vertical intervals isolated by inflatable packers, and the quantities of water accepted by each interval at several steps of increasing, then decreasing, pressure were noted. Pre-subsidence hole T401 was 213 m deep, and tested in summer 1988 using 6-m injection intervals. Post-subsidence hole T402 was drilled in late summer 1989, approximately 30 m west of T401 because of site problems, and drilling was stopped at 158 m, because of extremely fractured conditions. Tests in T402 were conducted using 3-m injection intervals. Both holes were tested completely through the sandstone and at selected intervals in lower zones. Packer test results were analyzed using a Hvorslev (1951) method verified for packer testing by Bliss and Rushton (1984) and Braester and Thunvik (1984). The packer tests are more fully described in Booth and Spande (1992); geotechnical studies conducted on the boreholes and cores are described by Mehnert and others (1994).

Pumping tests

Sixteen pumping tests of various durations and rates were conducted in well P350 between 1988 and 1994 (Table 2). Water levels were monitored in the test well and observation piezometers by transducers and/or manual drop-lines. The test methods and instrumentation were

Table 1
Piezometer construction details. (Details for P302–P350 from Mehnert and others 1994; for P410–P411 from Miller 1996.)

piezometer	elevation of top m AMSL		screened interval m below top	comment
	pre-subsidence	post-subsidence		
P302	134.44	133.88	41.45–44.50	tension zone
P303	134.28	132.15	31.09–34.14	inner area
P304	134.10	132.04	43.28–46.33	inner area
P306	133.88	133.93	44.20–47.24	152 m N of panel
P350	133.78	131.66	21.95–47.55	centerline, open test well
P410	N/A	131.53	43.36–46.04	inner area
P411	N/A	134.07	43.91–46.96	tension zone

Table 2
Details of pumping tests

test	date	pump time min	pump rate l/s	maximum drawdown m	comment
1	10/88	brief	0.418	n/a	pre-subsidence
2	10/88	13	0.440	8.41	unconfined
3	10/88	23	0.347	7.11	(Spande 1990)
4	10/88	68	0.322	n/a	
5	1/89	239	0.300	9.24	
6	3/90	32	0.332	3.48	post-subsidence
7	3/90	66	0.316	4.53	unconfined
8	3/90	258	0.328	4.47	(Spande 1990)
9	3/92	brief	n/a	n/a	post-subsidence
10	3/92	177	0.394	7.86	confined
11	7/92	1440	0.316	3.59	(Pattee 1994)
12	7/93	155	0.589	4.97	whole aquifer
13	8/93	1241	0.575	5.78	(Miller 1996)
14	10/93	1409	0.896	10.51	
15	3/94	1420	0.937	14.86	lower sandstone only
16	3/94	1281	0.576	n/a	(Miller 1996)

progressively changed as questions and problems arose; later tests used more accurate transducers and a more powerful pump.

Hydraulic test results

Pre-subsidence hydraulic conductivities of the Mt Carmel Sandstone over the panel were determined by slug tests to be of the order 10^{-5}–10^{-4} cm/s. The pre-subsidence packer tests indicated conductivities of the order 10^{-7}–10^{-4} cm/s, with a geometric mean of 4.7×10^{-5} cm/s. The post-subsidence packer conductivities were of the order 10^{-6}–10^{-3} cm/s, with a geometric mean 9.1×10^{-4} cm/s, and thus indicate approximately an order of magnitude increase in conductivity over the centerline. The post-subsidence values appear to have increased to 10^{-3} cm/s in the tension-margin zone, but not in the inner zone (Table 3); however, these P410 and P411 results are probably underestimates, as already noted. Otherwise, the slug and packer test results are broadly consistent.

The use of multiple test methods and several boreholes provides a good overall picture of the hydraulic properties of the aquifer. Hydraulic conductivities determined from slug and pumping tests are summarized in Table 3. Even before subsidence, the aquifer was heterogeneous, with approximately two orders of magnitude variation in conductivity values between piezometers from place to place. For example, the slug test conductivity in piezometer P306 in the unsubsided area was very low (10^{-7}–10^{-6} cm/s).

There were also substantial differences in conductivity values obtained for the same boreholes from different tests. These may be attributed to inadequacies of the analytical models, errors in test methods (such as borehole effects in slug tests), and differences in the areas and vertical intervals of the aquifer sampled by the different methods. The slug and packer tests sample limited intervals in the immediate vicinity of the test holes, whereas pumping tests sample larger vertical sections over wider areas, and pumping tests of different durations and rates sample different areas of the aquifer. Five pumping tests were conducted before subsidence, of which the first three were brief and served mainly to develop the well. Recovery analysis of the test well data from tests 4 and 5 (68 and 239 min long, Table 2) produced different conductivity values: 1.7×10^{-5} and 3.3×10^{-6} cm/s, respectively (Table 3). Whether this pre-subsidence decrease is real or a reflection of the region of aquifer sampled is unknown.

Increasingly greater values of conductivity were shown by the post-subsidence tests 1 year (3.7×10^{-5} cm/s from test 8), 3 years (5.4×10^{-5} from test 11), and 4 years (9.6×10^{-5} from test 13) after mining. This may indicate a long-term development of the well with pumping as well as the sudden increase in permeability that occurred with subsidence. Comparing tests of similar duration just before to shortly after subsidence, the specific capacity of the well increased from 0.032 L s^{-1} m^{-1} in test 5 to 0.073 L s^{-1} m^{-1} in test 8, a significant change. During the 1988–1990 period the aquifer was unconfined and test results were analyzed (Spande 1990) by the Neumann (1975) method. The aquifer recovered to a confined state in 1991, and tests 10 and 11 were analyzed (Pattee 1994) by the Hantush (1956) method for leaky confined aquifers. Since the leaky response also resembles stages of other aquifer conditions, Miller (1996) analyzed the results

Table 3
Hydraulic conductivity values from representative slug and pump tests (cm/s)

test	date	location relative to subsidence trough over panel 4				
		centerline	interior area		tension zone	outside
pre-subsidence tests (Spande 1990)						
		P350	P304	P303	P302	P306
slug	10/88	—	3.0E-4	1.8E-5	2.1E-4	1.4E-6
slug	2/89	—	1.7E-4	1.8E-5	2.0E-4	—
PT4	10/88	1.7E-5	3.9E-6	1.3E-4	3.0E-4	—
PT5	1/89	3.3E-6	5.1E-5	2.9E-5	5.6E-5	—
post-subsidence tests (Spande 1990; Pattee 1994; Miller 1996)						
PT7	3/90	3.4E-5	—	—	—	—
PT8	3/90	3.3E-5	—	—	—	—
			P410		P411	P306
PT11	7/92	5.4E-5	4.4E-4		1.0E-2	
slug	1992	—	2.2E-4		1.4E-3	5.1E-7
post-subsidence tests (Miller 1996)						
		P350	P410	Transboundary from P410 & P350	P411	
PT13	8/93	9.6E-5	3.0E-3	1.7E-2 & 3.8E-3	2.0E-3	
PT14	10/93	9.4E-5	3.0E-3	1.7E-2 & 2.8E-3	2.1E-3	
PT15	3/94	lower sandstone only	2.5E-3	2.7E-2	3.0E-3	
PT16	3/94		3.0E-3	2.2E-2	2.0E-3	
numerical model calibration (Miller 1996)						
			inner area		tension zone	outside
east-west			8.6E-5		9.7E-3	7.6E-6
north-south			6.5E-4		7.2E-2	5.7E-5

of later, longer tests (Table 2) by alternative models (unconfined, layered aquifer, double porosity, bounded). He also tested the hydraulic separation of the two sandstone benches by pumping the lower bench while an inflated packer was set between them. He concluded that the aquifer is a confined, single-porosity system in which the two sandstone benches behave locally as separate aquifers. Only the upper bench could receive leakage (if any) from the shale; the more transmissive lower bench, and the aquifer as a whole, behave in a confined manner. Drawdown responses were strongly influenced by permeability discontinuity boundaries, and analysis by the Fenske (1984) method proved most suitable.

In the later post-subsidence tests, piezometers P410 in the inner trough area and P411 in the marginal tension zone provided data for determination of hydraulic conductivities (Table 3) and storativities (Table 4). Piezometers P304 and P302 were in the corresponding positions before subsidence. Piezometer P303, in an intermediate position, was the only piezometer screened in the upper, finer part of the lower sandstone bench, which is reflected in its lower hydraulic conductivity. As Table 3

Table 4
Storativity values determined from pump tests

test	date	interior area		tension zone	comment
		P304	P303	P302	
PT4	10/88	4.4E-5	3.6E-4	1.1E-4	Spande (1990)
PT5	1/89	2.0E-4	2.0E-4	3.9E-5	
		P410		P411	
PT11	7/92	3.4E-3		2.4E-3	Pattee (1994)
PT13	8/93	6.4E-4		3.6E-3	Miller (1996)
PT14	10/93	5.6E-4		2.8E-4	
PT15	3/94	1.0E-4		9.0E-4	
PT16	3/94	9.2E-5		1.9E-4	
model calibration		2.5E-5		2.5E-3	
model calibration		undisturbed zone outside trough: 7.0E-5			

shows, there were considerable variations in conductivity between different piezometers and between different tests. Overall, however, there was a general increase in permeability from before to after subsidence, typically of one to two orders of magnitude. The storativities (Table 4) also show a moderate increase, from the 10^{-4} to the 10^{-3} range. The hydraulic properties appear to have increased most in the marginal tension zone, as expected from the subsidence deformation pattern.

In a further examination of the bounded aquifer model, Miller (1996) used a commercial software version of MODFLOW (McDonald and Harbaugh 1988) to simulate drawdown from selected tests. The hydraulic conductivity values used in the final calibrated simulations are also included on Table 3. They correspond well with the overall pattern, but are markedly anisotropic. The higher values in the north-south direction may be due to the transverse orientation of subsidence fractures in the central trough area where the pumping well was located.

In summary, the hydraulic tests present a model of a heterogeneous aquifer of low to moderate permeability, in which a new spatial permeability configuration develops over the longwall panel: a zone of slightly enhanced permeability in the inner subsidence trough, a zone of more enhanced permeability in the marginal tension zone, and an undisturbed region of naturally low permeability outside the panel. Storativity changed similarly.

Potentiometric response

The ISGS had observed that water levels in the sandstone over panel 3 declined as the mine face approached and reached a minimum during the tensional early phase of subsidence, and gradually recovered after the face had passed (Mehnert and others 1994) . The sandstone piezometers over panel 4 responded similarly to the mining of adjacent panel 3, declining from initial water levels around 20 m below ground to lows of about 34 m coincident with the nearest approach of the panel 3 face, then partly recovering through the Fall of 1988.

The hydrographs of the water levels in the panel 4 sandstone piezometers during and shortly after the active mining of panels 3 and 4 are shown in Fig. 3. When panel 4 started mining in November 1988, the water levels began a second gradual decline, which steepened as the mine face approached. When the site subsided (9–10, February 1989), the levels fell rapidly to a low of about 43 m below ground. They recovered slightly a few days after subsidence.

The primary response to subsidence is the rapid drop to a potentiometric minimum that occurs in the actively subsiding zone. This is attributable to the rapid increase in storage void volume caused by the dilation of fractures, joints, and bedding planes. The earlier, gradual decline in head observed at piezometers ahead of the subsidence front is a secondary response to the approaching potentiometric low. It can be considered equivalent to a drawdown effect spreading out through the aquifer from the subsiding zone. The rate of advance transmission of this effect depends on the hydraulic properties of the geologic unit. It was observed (Booth and Spande 1992) that the "drawdown" responses in the less transmissive shale units occurred abruptly just before subsidence, rather than gradually as they did in the aquifer.

The partial recovery shortly after subsidence coincides with the ground compressional phase and is attributable to the partial reclosure of fractures and bedding planes. The aquifer was separated from the mine by thick confining strata, and its behavior is considered to be independent of any effects of mine inflow, which was in any case very minor at this panel.

Because of piezometer damage to the piezometers, water-level monitoring over the panel in the year after undermining was limited to manual drop-line measurements in test well P350. New piezometers P410 (inner trough) and P411 (tension zone) were drilled into the lower sandstone in August 1991, and monitored with transducers in 1991–1992 and manually until 1995. The level in P350 continued to rise until by spring 1995 it was about 12 m below ground. This more-than-full recovery indicates that the 20-m-deep water levels first measured in 1988 had already been depressed by the mining of earlier panels.

Figure 4 shows the later hydrographs for P350, P410, P411, and off-panel piezometer P306, expressed as head elevations. The parallel hydrographs of the panel piezometers and well P350 show that the recovery is a general feature across the panel and not just an artifact of the well. The head in well P350, open to the whole aquifer, is approximately 2.4 m higher than the heads in P410 and P411, open only to the lower sandstone. This difference is consistent with the head differences between the upper and lower benches measured during the later pump tests when the packer was placed in the intervening shale-siltstone unit. The heads in P410 and P411 are almost identical, with differences no greater than about 0.04 m, indicating that the lateral hydraulic gradient across the panel is low. The head in piezometer P306, in the undisturbed zone north of the panel, was about 1.5 m higher than heads over the panel in 1991, but the head difference decreased to about 0.15 m by August 1992 (when P306 readings stopped) as the heads over the panel recovered.

Whereas the short-term partial recovery just after subsidence was caused by recompressional stress, the long-term recovery was due to true recharge of the aquifer. Water flowed back in to fill the subsidence-induced "cone of depression". Some of this recharge could be derived from leakage through the overlying shale, particularly in the more heavily fractured tension zone. However, considering the substantial transmissivity of the aquifer, the hydraulic confinement of at least the lower bench, and the probably low vertical permeability of the shales, the recharge is more likely to be derived mostly from lateral flow through the aquifer from regions of higher head outside the subsided area.

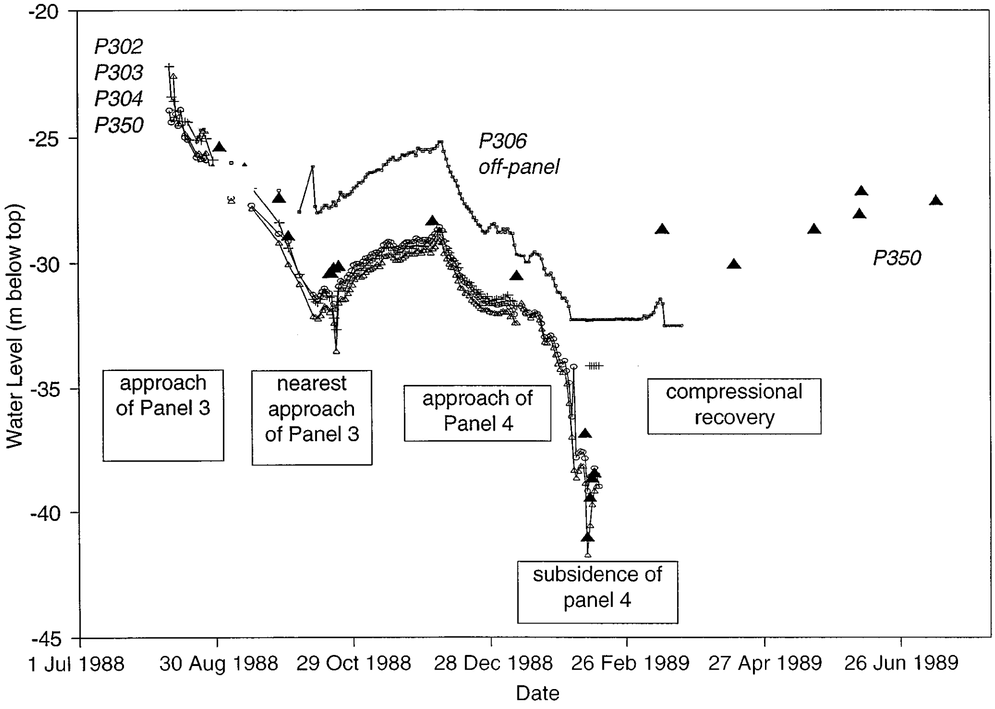

Fig. 3
Water levels in panel-4 sandstone piezometers during mining, 1988–1989

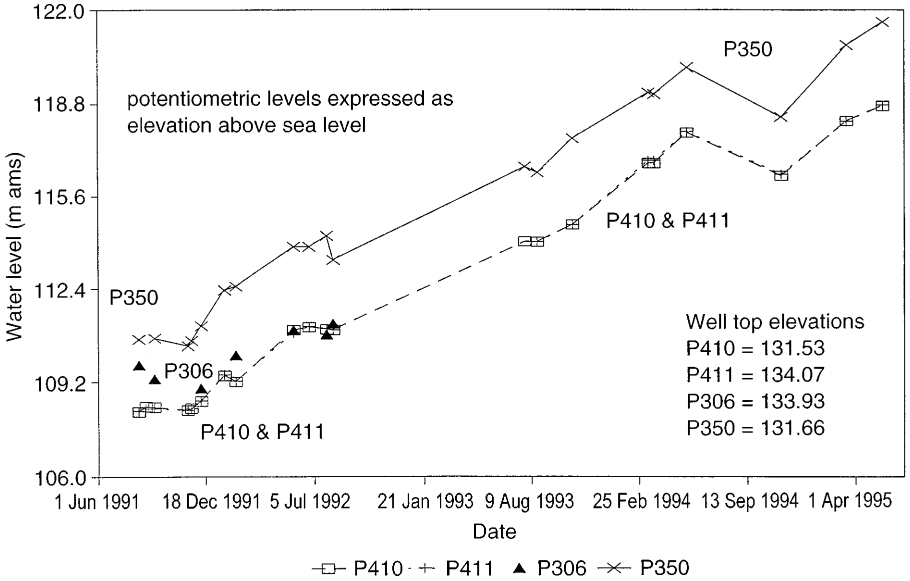

Fig. 4
Long-term water-level recovery in panel-4 piezometers and well

Changes in groundwater chemistry

Groundwater samples have been taken and analyzed at all major phases of this study [theses by Spande (1990), Pattee (1994), and Bertsch (in preparation)]. Methods of sampling (pumping and bailer) and analysis have varied throughout the study because of the changing availability of equipment. Samples were tested in the field for pH, alkalinity, temperature, and specific conductivity, and in the laboratory for major anions and cations. Cation analysis (of acidized samples) was made either by DC plasma spectrometer or x-ray fluoresence spectrometer; anion analysis was by titration, specific ion electrode, spectrophotometer, or anion chromatography.

Selected representative analyses of water from the shale and the sandstone are given in Table 5. Samples were also taken from drift and combination shale-drift wells. Water in the drift was fresh (total dissolved solids less than 600 mg/l) and of mixed cation, sulfate-dominant type. Water in the shale is represented by analyses from wells W3 and W5D (Table 5). W3, located about 200 m north of panel 4, was 11.6 m deep; W5D, located on the northern edge of panel 3, was 19 m deep. Both wells produced brackish water of mixed cation, sulfate type. The

Table 5
Representative analyses of water samples from shale and sandstone (N.B. CBE = charge balance error)

Well & date	cond uS/cm	pH	Temp	Ca	Mg	Fe	K	Na	HC03	Cl	N03	S04	TDS	CBE %
							concentration mg/l							
W3 – shale														
28 Jul 1988	3990	7.21	14.30	287.5	245.6	0.00	4.16	262.0	430.6	32.6	0.00	1783.7	3046.9	1.06
10 Jan 1989	3580	7.48	14.80	191.6	137.8	0.44	5.84	198.2	322.0	43.2	15.50	1207.2	2122.6	−3.51
15 May 1989	2880	7.01	14.00	100.0	66.7	0.32	6.26	111.1	232.0	17.2	5.90	485.9	1026.1	3.49
11 Jul 1989	1600	6.81	14.30	147.0	115.7	0.00	0.92	192.1	330.0	37.4	10.4	697.3	1530.8	8.80
17 Sep 1989	4000	6.93	15.60	382.0	274.6	0.00	4.95	295.9	488.0	23.6	0.00	2161.8	3632.1	0.96
23 Nov 1991	1470	n/a	14.80	186.4	157.4	0.44	2.93	224.4	318.0	59.6	15.4	1053.6	2018.3	4.94
11 Aug 1992	4050	7.17	15.70	284.9	218.3	0.00	1.33	250.3	401.2	87.6	7.92	1590.7	2842.0	0.92
15 Nov 1994	3280	7.18	14.80	297.4	208.8	0.04	1.97	257.2	509.5	75.5	17.93	1528.7	2802.2	0.90
16 Mar 1995	2680	7.08	14.70	278.2	180.8	0.12	1.50	244.1	492.5	50.7	19.72	1436.9	2616.4	−0.36
W5D – shale														
15 Jul 1988	4740	6.55	14.10	513.8	309.7	1.94	9.10	318.0	504.8	24.8	0.00	2961.7	4649.17	−3.78
10 Jan 1989	1970	6.97	14.10	227.6	107.0	0.00	9.07	90.7	168.0	30.8	64.0	1099.7	1797.9	−6.18
10 Feb 1989	3660	6.80	14.10	377.5	177.5	0.00	7.89	139.9	224.0	49.0	120.0	1307.0	2403.8	7.42
15 May 1989	3710	7.00	14.10	417.8	203.6	0.00	5.21	187.4	332.0	41.2	92.0	1859.9	3140.5	−0.97
11 Jul 1989	3500	6.47	14.20	456.1	219.4	0.00	3.57	204.4	314.0	97.4	91.0	1680.9	3067.4	−4.47
17 Sep 1989	3600	6.94	15.30	425.6	212.3	0.00	5.24	181.1	346.0	109.0	0.00	1946.9	3227.6	−2.61
22 Nov 1991	3290	n/a	14.40	408.8	233.6	0.00	5.00	213.7	274.0	106.4	62.92	1690.52	2995.2	5.77
9 Aug 1992	3530	6.87	15.50	423.5	244.0	0.00	4.68	188.4	290.6	125.6	68.2	1781.4	3126.4	3.13
15 Nov 1994	2770	7.21	13.70	296.3	175.0	0.00	6.97	157.6	352.3	51.4	28.83	1571.5	2578.5	−5.39
16 Mar 1995	3160	7.11	15.50	375.4	231.0	0.10	4.09	209.0	480.0	119.5	8.19	1954.0	3295.6	−5.12
W18 – sandstone														
15 Nov 1994	1200	7.83	14.30	7.20	3.82	0.00	0.00	293.1	639.4	72.66	0.00	1.41	902.4	3.38
22 Mar 1995	1249	8.02	14.00	5.54	5.03	0.00	0.55	303.3	669.7	53.19	0.00	4.06	920.9	5.17
P350 – sandstone														
30 Aug 1988	1580	8.38	14.80	4.21	2.39	0.57	3.73	384.7	560.0	5.60	0.00	260.4	1221.8	7.86
10 Jan 1989	1380	8.12	13.90	1.35	0.99	0.00	1.61	387.4	574.0	11.20	4.60	178.15	1159.4	11.57
22 Nov 1991	3030	n/a	14.40	56.36	53.87	0.00	2.43	725.9	621.0	47.6	0.00	1106.3	2613.8	5.99
14 Febr 1992	n/a	7.08	n/a	54.69	60.0	1.19	5.19	645.5	628.0	37.60	0.00	1090.5	2523.2	2.80
10 Aug 1992	2880	7.41	15.30	56.68	36.94	1.27	2.12	711.0	533.0	44.8	0.00	1233.9	2620.5	1.85
25 May 1994	2760	7.98	15.30	51.97	80.56	0.00	1.30	731.9	766.2	47.6	0.00	1078.2	2619.5	6.13
19 Aug 1994	2200	8.31	17.40	26.42	27.42	0.16	2.15	565.6	657.6	22.92	2.86	802.2	1990.1	0.32
16 Mar 1995	3400	7.37	14.60	39.69	n/a	0.00	3.38	660.2	681.3	30.12	0.00	1067.8	2401.0	−0.17
P411 – sandstone														
10 Aug 1992	1950	6.99	14.30	188.2	98.86	0.00	9.10	119.4	350.0	50.40	0.00	792.7	1608.8	−1.46
22 Mar 1995	1249	7.50	15.60	150.2	94.44	0.00	5.39	220.7	632.3	27.67	22.69	677.9	1719.4	−1.00

TDS values in samples taken in summer 1988 were in the 3000+ mg/l range for shallower well W3 and in the 4000+ mg/l range for W5D. After mining, in the long term the water exhibited a slight reduction in salinity that may reflect increased drift recharge or simply changed sampling method; however, it remained a brackish high-sulfate water.

The Mt Carmel Sandstone aquifer was sampled before and after mining in well P350, open through the whole aquifer, and during the later post-mining period also in piezometer P411, screened in the lower sandstone. (Samples from the other piezometer P410 were unreliable because an obstruction restricted purging and sampling to the uppermost part of the water column.) Samples were also obtained late in the study from well W18, a 60-m-deep sandstone well in the unmined area approximately 5 km to the east of the site.

The native water in the aquifer is represented by samples from well W18 and pre-subsidence P350 (Table 5). These were both sodium-bicarbonate dominant, slightly brackish in P350 (TDS around 1200 mg/l) and fresher in W18 (900 mg/l). P350 had relatively high (200 mg/l) sulfate, whereas W18 had almost none. During the post-mining recovery of water levels in the sandstone, the water in P350 became more brackish (TDS in the range 1990–2620 mg/l) with high (800–1273 mg/l) sulfates - a clear deterioration in quality. Bicarbonate levels remained approximately the same, but sodium increased from less than 400 mg/l to 600 mg/l or above. The samples from the piezometer P411 were slightly fresher (TDS 1481–1719 mg/l) than those from P350.

The geochemical changes are evidently due to water flowing back into the aquifer following subsidence. There are two likely sources for the recharge water: leakage from the overlying shale and flow through the aquifer itself. The chemical changes themselves do not clearly discriminate between these sources. The shale water contains high sulfate, but water flowing back through the aquifer could also be liberating sulfate from sulfide minerals contained in the sandstone (Bertsch, in preparation). The later water samples from the sandstone were slightly oxidizing; comparable pre-subsidence data were not available. Sodium was lower in the shale water than in the sandstone water, but could conceivably have been released by cation exchange (for calcium) on clays during leakage from the shale.

Although the chemical evidence is ambiguous, the hydraulic tests indicate that leakage from the shale would affect only the upper sandstone, and that the lower sandstone would be recharged solely by flow through the aquifer. This may explain why the water chemistry is more brackish at well P350, open to the whole aquifer and to recharge from both the shale and the sandstone, than at P411, screened in the lower sandstone and isolated from the shale.

Conclusions

Longwall mine subsidence has significant impacts on shallow bedrock aquifers. The primary impacts are a drop in well water levels caused by dilation of fractures, joints, and bedding planes, and permeability changes which cause longer-term changes in the groundwater flow patterns. The local geological setting and initial aquifer conditions dictate whether there are also water-level recoveries, changes in groundwater chemistry, and positive or negative overall impacts.

Permeabilities increase in the subsidence trough area, which therefore becomes a preferential pathway for groundwater flow, especially along its margins where tensile effects are most marked. In coalfield regions with significant structural and topographic relief, such as the Appalachian Plateau, the result can be that shallow aquifers drain more effectively toward the downgradient zones - resulting in reduced hydraulic gradients, lowered heads in up-gradient sections, and increased spring discharge at downgradient outcrops, as indicated by several other studies.

The Illinois Basin coalfield has low relief and a glacial drift cover. At a site such as Jefferson County, the sandstone aquifer does not outcrop, and subsidence produces a sharply bounded, closed-end "bath-tub" zone in which the aquifer is physically enhanced and well yields increased. This is potentially a substantial area of enhanced aquifer, considering that each longwall panel has an area of around 40 ha.

Physical enhancement means improved well yields only if the water levels in the aquifer recover from the transient depression caused by storage changes during subsidence. Recovery depends on the "rechargeability" of the aquifer - the combination of its transmissivity and access to sources of recharge. Where these are relatively good, as in the Jefferson County case, water-level recovery occurs.

Physical enhancement of the aquifer is of less value if the water deteriorates in quality. At the Jefferson County site, deterioration resulted in a change from a slightly brackish to a more brackish (TDS over 2000 mg/l) water, coupled with an increase in sulfates to well above potable levels. This may be an almost inevitable consequence of the movement of large volumes of recharge water into the affected area. Nevertheless, if one considers that on-site domestic water-treatment systems are now available for water of this brackish quality, the chemical deterioration does not necessarily make the resource unusable. The effect of longwall subsidence, even in this case, may ultimately be positive.

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References

Aston TRC, Singh RN (1983) A reappraisal of investigations into strata permeability changes associated with longwall mining. Int J Mine Water 2:1–14

Bliss JC, Rushton KR (1984) The reliability of packer tests for estimating the hydraulic conductivity of aquifers. Q J Eng Geol 17:81–91

Booth CJ (1995) Aquifer improvement due to mine subsidence: conditions based on hydrogeological studies in Illinois. In: Abstracts with programs, Geol Soc America Annual Meeting, New Orleans, 6–9 November. GSA, Boulder, CO, p 101

Booth CJ (1996) Long-term potentiometric changes in sandstone aquifers due to longwall mining, Illinois. In: Program and Abstracts. 41st Annual Midwest Groundwater Conference, Lexington, KY, September. Kentucky Geol Surv. University of Kentucky, Lexington, pp 44–45

Booth CJ, Spande ED (1992) Potentiometric and aquifer property changes above subsiding longwall mine panels, Illinois Basin coalfield. Ground Water 30:362–368

Bouwer H (1989) The Bouwer and Rice slug test - an update. Ground Water 27:304–309

Bouwer H, Rice RC (1976) A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resour Res 12:423–428

Braester C, Thunvik R (1984) Determination of formation permeability by double-packer tests. J Hydrol 72:375–389

Dixon DY, Rauch HW (1988) Study of quantitative impacts to ground water associated with longwall coal mining at three mine sites in the northern West Virginia area. In: Peng SS (ed) Proc 7th Int Conf Ground control in mining, West Virginia University, August. West Virginia University, Morgantown, WV, pp 321–335

Fenske P (1984) Unsteady drawdown in the presence of a linear discontinuity. In: Rosenshein J, Bennett G (eds) Groundwater hydraulics. Am Geophys Union, Washington DC, pp 125–145

Hantush MS (1956) Analysis of data from pumping tests in leaky aquifers. Trans Am Geophys Union 37:702–714

Hill JG, Price DR (1983) The impact of deep mining on an overlying aquifer in western Pennsylvania. Ground Water Monit Rev 3:138–143

Hvorslev MJ (1951) Time lag and soil permeability in groundwater observations. Bull 36, Waterways Experiment Station, US Army Corps of Engineers, Vicksburg, Miss

Johnson KL (1992) Influence of topography on the effects of longwall mining on shallow aquifers in the Appalachian coal field. In: Peng SS (ed) Proc 3rd Worksh Surface subsidence due to underground mining, Morgantown, WV, 1–4 June West Virginia University, Morgantown, WV, pp 197–203

Kelleher, JT, Van Roosendaal, DJ Mehnert BB, Brutches DF, Bauer RA (1991) Overburden deformation and hydrologic changes due to longwall coal mine subsidence on the Illinois basis. In: Johnson AI (ed) Land subsidence. Proc 4th Int Symp Land subsidence, Houston, TX 12–17 May. IAHS Publication No. 200, pp 1985–204

Kratzsch H (1986) Mining subsidence engineering. Environ Geol Water Sci. 8:133–136

Matetic RJ, Trevits MA (1992) Longwall mining and its effect on ground water quantity and quality at a mine site in the northern Appalachian coalfield. In: Proc AGWSE Focus Conf Eastern regional ground water issues, 13–15 October, Newton, MA. Ground Water Managment Book 13. AGNSE, Columbus, OH, pp 573–587

McDonald M, Harbaugh A (1988) A modular three-dimensional finite-difference ground-water flow model. US Geol Surv Tech Water Resour Invs, Book 6, Chap A1.

Mehnert BB, Van Roosendaal DJ, Bauer RA, Brutcher DF (1990) Effects of longwall mine subsidence on overburden fracturing and hydrology in Illinois. In: Elifrits CD (ed) Mine subsidence - prediction and control. Proc Assoc Eng Geol 33d Annual Meeting, Pittsburgh, Oct, pp 105–112

Mehnert BB, Van Roosendaal DJ, Bauer RA, DeMaris PJ, Kawamura N (1994) Final report of subsidence investigations at the Rend Lake site, Jefferson County, Illinois. Illinois State Geological Survey, US Dept of the Interior, Coop Agreement CO267001

Miller JD (1996) Hydrogeologic characterization of a heterogeneous sandstone aquifer overlying a high extraction longwall coal mine. MS thesis, Northern Illinois University, DeKalb, IL

Moebs NM, Barton TN (1985) Short-term effects of longwall mining on shallow water sources In: Mine subsidence control. Proc Bureau of Mines Tech Transfer Seminar, Pittsburgh, PA, September 19. US Bureau Mines Info Circ 9042, pp 13–24

Neumann SP (1975) Analysis of pumping test data from anisotropic unconfined aquifers considering delayed gravity response. Water Resour Res 11:329–342

Pattee CT (1994) Long-term hydrogeologic impact of longwall subsidence on a shallow bedrock aquifer in Illinois. MS thesis, Northern Illinois University, DeKalb, IL

Pattee CT, Booth CJ (1992) Long-term hydraulic changes in a shallow confined aquifer induced by longwall coal mine subsidence, Illinois. Geol Soc Am, North-Central Section Meeting, April 30: Abstracts with Programs 24 (4): 59

Pauvlik CM, Esling SP (1987) The effects of longwall mining subsidence on the groundwater conditions of a shallow unconfined aquitard in southern Illinois. In: Proc 1987 Nat Symp Mining, hydrology, sedimentology and reclamation. Springfield IL, 7–11 December. University of Kentucky, UKY BU145, Lexington, KY, pp 189–196

Schulz RA (1988) Ground-water hydrology of Marshall County, West Virginia, with emphasis on the effects of longwall coal mining. US Geol Surv Water Resour Inv Rep 88–4006

Spande ED (1990) Effects of longwall-induced subsidence on hydraulic properties at a site in Jefferson County, Illinois. MS thesis, Northern Illinois University, Dekalb, IL

Tieman GE, Rauch HW (1987) Study of dewatering effects at an underground longwall mining site in the Pittsburgh seam of the northern Appalachian coalfield. In: Eastern Coal Mine Geomechanics, US Bureau Mines Info Circ 9137, pp 72–89

Trent BA, Bauer RA, DeMaris PJ, Kawamura N (1996) Findings and practical applications from the Illinois Mine Subsidence Research Program, 1985–1993: final report to Illinois Clean Coal Institute: IMSRP XII

US DEPARTMENT OF THE INTERIOR (1981) GROUND WATER MANUAL: A WATER RESOURCES TECHNICAL PUBLICATION (REVISED EDN). WILEY, NEW YORK

Van Roosendaal DJ, Brutcher DF, Mehnert BB, Kelleher JT, Bauer RA (1990) Overburden deformation and hydrologic changes due to longwall mine subsidence in illinois. In: Chugh YP (ed) Proc 3d Conf Ground control problems in the Illinois Coal Basin Southern Illinois Univ. Carbondale, August, pp 73–82

Walker JS (1988) Case-study of the effects of longwall-mining-induced subsidence on shallow ground water sources in the northern Appalachian coalfield. US Bureau Mines Rep Inv 9198