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RECOVERY OF GROUNDWATER LEVELS AFTER LONGWALL MINING

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ABSTRACT

Longwall underground coal mining lowers water levels in shallow bedrock aquifers overlying the mine, due mainly to increases in fracture porosity caused by subsidence. The water levels commonly recover partially or wholly after mining, but recovery is less consistent and less predictable than the initial decline. This paper examines the recovery after longwall mining reported in US studies and observed at two sites in Illinois, USA. The two sites were similar in low topographic relief and general strata sequence, but had different recovery behavior. Full recovery occurred at one site (Jefferson) where the sandstone aquifer was thicker and more transmissive. At the other site (Saline), there was no recovery, except locally where a sand-and-gravel unit recharged the aquifer. Based on the studies, factors in predicting recovery include topographic setting, hydraulic separation above the mine and caved zone, aquifer transmissivity, and continuity with recharge sources.

INTRODUCTION

This paper examines the recovery of groundwater levels after the completion of longwall underground coal mining. Recovery is less predictable than the groundwater declines which occur at the time of mining, in wells over and near longwall panels.

The initial response is well known. During longwall mining, immediate subsidence causes fracturing and bedding separation in overlying strata, increasing the secondary porosity and permeability of the strata and changing groundwater storage and flow characteristics. There are several deformational zones above a longwall mine: a deep caved zone of very fractured, dewatered strata; an intermediate confining zone of coherently subsided strata that hydraulically separates shallow aquifers from the mine; the shallow bedrock zone in which aquifers are affected by fracturing but not by drainage to the mine; and in some cases an unconsolidated cover which is usually not very affected by subsidence. The water levels in the shallow bedrock in the actively subsiding zone over the mine face drop sharply due to the increase in secondary porosity. From this potentiometric low, a potentiometric depression, or drawdown, spreads out laterally, and is normally the first response observed in piezometers ahead of mining. In less transmissive units, the drawdown is very localized and sudden, whereas in more transmissive units it is more widespread and gradual.

The recovery of water levels over a completed mining operation is probably a more important long-term consideration than the initial depression, since it is more costly and difficult to replace a permanent loss than to provide substitute water supplies for a short-term loss. However, the recovery is less well understood, and it is difficult to predict if (and when and how much) a particular well or aquifer zone will recover. In this paper, we review several studies of recovery conducted in the US Appalachian coalfield, and summarize recovery observations from our studies at two sites in the Illinois coalfield in the US Midwest region.

REVIEW OF STUDIES IN THE APPALACHIAN COALFIELD, USA

The Appalachian Coalfield of the eastern USA contains mainly bituminous coal resources of Pennsylvanian age. Several hydrological studies of longwall mining have been conducted in the Northern Appalachian region, which is mostly characterized by moderate topographic relief (typically 100-200 m), longwall mining depths of 100 to 400 m, gently dipping strata, and mostly poorly permeable sequences of interbedded shales, siltstones, sandstones, minor limestones, underclays and coal. Shallow, thin sandstones form local aquifers. The potentiometric response to mining follows the model described above, but is affected by the topography. Wells and springs located on hilltops and hillsides are usually more severely impacted by undermining than those located in valleys (Johnson and Owili-Eger, 1987; Tieman et al., 1992; Leavitt and Gibbens, 1992; Werner and Hempel, 1992; Johnson, 1992), and recovery is generally better in valley settings.

As Werner and Hempel (1992) commented, reports of recoveries after longwall mining are inconsistent. Walker (1988) observed that, of ten shallow wells over or near four adjacent panels, only one well, over the center of a panel, did not exhibit some recovery. In contrast, Cifelli and Rauch (1986), in a study in West Virginia, found that of 19 wells (30-100 m deep) directly over total extraction mining, only one showed any significant recovery; they also observed a correlation between numbers of wells impacted and percentage of recharge area undermined.

In one study of two adjacent panels, Matetic and Trevits (1990) found that the largest water-level fluctuations occurred in wells that were directly undermined, and that recovery occurred in all affected measurable wells. At other sites, Matetic and Trevits (1991, 1992) and Trevits and Matetic (1991) observed that water levels in shallow aquifers declined substantially when the sites were undermined, but recovery began before subsidence was completed, starting about the time of maximum compressive strain, or approximately when the face had progressed beyond the well by about 40 % of the overburden thickness.

Topographic setting and depth of the well relative to the deep caved zone affect recovery. Johnson and Owili-Eger (1987), in a study of dewatered wells in "perched" aquifers at a hilltop location, observed that two wells 182 m deep (into the caving zone) never recovered, whereas two 57-m-deep wells recovered within 6 months. They concluded that the recovery occurred after the fractured confining layers between the various aquifers had resealed. Leavitt and Gibbens (1992) examined the responses of 174 domestic water supplies to longwall mining of the Pittsburgh coal seam and determined that, once over about 90 m, the overburden thickness is not a factor in well response, but topography is dominant, with significantly more of the valley wells recovering than hilltop wells. Tieman et al. (1992) observed that longwall-impacted spring supplies recovered better near stream channels, and that lost spring waters were not draining to the mine but were simply discharging downgradient.

Rauch (1989) concluded that dewatered shallow wells in valley locations above the mine recovered rapidly (in hours to weeks), whereas wells on steep hillsides took months to recover and hillside springs had poor to no recovery. However, where the panel width is more than twice the overburden width, wells do not significantly recover within a few years, unless they are located near a stream. Rauch noted that many supplies which do not recover within a measurable time will nevertheless ultimately do so after the mine is abandoned and flooded.

DESCRIPTION OF STUDY SITES IN ILLINOIS

From 1988 to 1995, Northern Illinois University (NIU) and the Illinois State Geological Survey (ISGS) conducted a comprehensive study into the geotechnical and hydrogeological effects of longwall mine subsidence at two sites in Jefferson and Saline Counties, south-central and south-eastern Illinois (Mehnert et al., 1994; Van Roosendaal et al., 1994; Trent et al., 1996; Booth et al., 1997). Studies at both sites included pumping, slug and packer tests to determine changes in hydraulic properties, monitoring of ground subsidence through monuments and of subsurface strains via borehole geotechnical methods, monitoring of water levels in piezometers and wells, and geochemical sampling of groundwater.

Both mines were into the Herrin Coal. Both sites are located in areas of gently rolling topography with local relief less than 15 m, in a humid continental climate with annual rainfall about 1 m. Both have a cover of glacial material overlying Pennsylvanian bedrock. The geological units are poorly permeable but include minor sandstone aquifers and thin, discontinuous sand and gravel deposits in the drift. Specific site information is summarized in Table 1.

Subsidence and potentiometric behavior at the Jefferson County Site

At the Jefferson site, a thin cover of glacial material (mainly till, some sand and gravel) overlies bedrock dominated by shales with minor sandstone, siltstone, clay, coal, and limes-

Item	**Jefferson Panel 4**	**Saline Panel 1**	**Saline Panel 5**
Date of mining	12/88 - 4/89	5/89 - 3/90	4/92 - 4/93
Depth of mining	220 m	122 m	91 m
Panel width	183 m	204 m	287 m
Av. mined-out thickness	2.9 m	2.0 m	1.94 m
Max ground subsidence	2.02 m	1.46 m	1.37 m
Period of monitoring	1988-1995	1989-1993	1992-1995
Study site undermined	2/89	12/89	1/93
Approximate strata thicknesses at the study sites			
Glacial cover	3-9 m	20 - 30 m	12 - 20 m
Upper confining shale	18 m	35 m	0-2 m
Sandstone aquifer	23-26 m	6 - 9 m	4 - 6 m
Lower confining unit	174 m	65-70 m	70 m

Table 1. Summary of study site information.

tone. The sequence includes a moderately permeable aquifer, the Mt Carmel Sandstone, overlain by a confining shale. This section of the mine consisted of four longwall panels, each about 183 m wide and over 1.5 km long. The study began after the mining of panels 1 and 2, so that the initial water levels were already affected by mining.

ISGS studies (Mehnert et al., 1994) during the mining of panel 3 in 1988 showed a progressive decline in water levels in the sandstone aquifer directly over the panel as the panel face approached, to a minimum during the maximum tensional subsidence phase. The water levels then started to recover immediately and, despite being affected by adjacent panel 4, eventually recovered a total of about 10 m in five years.

Our studies (Booth et al., 1997, 1998) over panel 4 showed that water levels in the sandstone declined due to the passage of adjacent panel 3, then recovered slightly until they started a gradual decline as panel 4 approached. They dropped rapidly at undermining to reach a total head loss of about 14 m compared to initially measured levels. Subsidence produced a heavily fractured zone extending to about 60 m above the mine, and substantial fracturing and bedding separations in the shallower bedrock, and also damage to most piezometers. Monitoring continued in a 15-cm-diameter well (P350) on the panel centerline, and in two new piezometers constructed into the sandstone over the inner panel and tension zone

Panel 4, and all mining in this section, was completed in April 1989. Figure 1 shows the water levels in well P350 from initial declines to final recovery. The recovery occurred in two distinct phases. First, there was a rapid partial recovery when the site entered the compressional phase, within a month of undermining. This is presumably related to the reclosure of fractures and bedding plane openings, and corresponds to the early recovery noted by Trevits and Matetic (1991) and Matetic and Trevits (1992) (see above). The water level in P350 then remained approximately stable for a year at about 25-30 m below ground, then began a rise that by 1995 reached 10 m below ground, well above the initial levels. A similar recovery was observed in the two new piezometers, indicating that it was a general phenomenon across the panel.

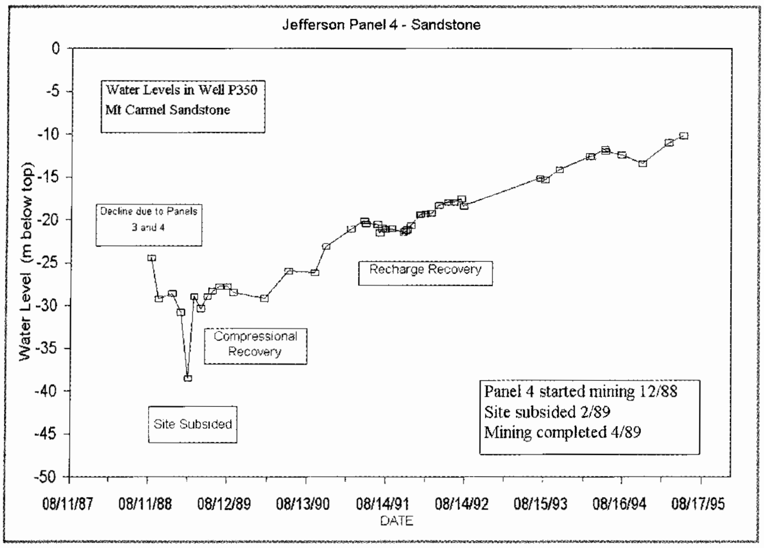

Figure 1. Water-level decline and recovery in Mt Carmel Sanstone, Jefferson Panel 4.

Durng recovery, the following phenomena were observed (Booth et al., 1998):

- Subsidence had increased the permeabilities of the aquifer (from pre-mining values in the range 10^{-7} m/s) by about an order of magnitude over the interior of the longwall panel, and by about two orders of magnitude in the tensional zone along the edges.
- Pumping tests conducted after mining indicated leakage of groundwater from the overlying confining shale, which had been fractured during subsidence, to the upper bench of the sandstone aquifer.
- Geochemical results showed a marked increase in total dissolved solids, especially sulfate levels, which could be attributed to both influx of poor quality water from the overlying shale and lateral flow of aggressive recharge water through the aquifer itself.

Subsidence and potentiometric behavior at the Saline County site

At the Saline site, the strata dip gently northwards and the cover of glacial materials (tills, lacustrine deposits, sand and gravel) varies considerably in thickness over an irregular bedrock surface. This section of the mine consisted of six longwall panels, variously 186-287 m wide and 2.2 - 3.1 km long, mined successively southwards. Studies were conducted over panels 1 and 5, mined in 1989-1990 and 1992-1993 (Booth et al., 1994, 1997).

Panel 1: At the panel 1 study site, the mine was overlain by about 90 m of bedrock and 30 m of glacial drift. The bedrock sequence was very poorly permeable, and even the shallow Trivoli Sandstone (less than 10 m thick, at depths around 55 m) had low permeabilities in the range 10^{-8} to 10^{-7} m/s. The deep caved zone extended only about 6 m above the mine, and the overburden subsided largely as a coherent mass with little internal vertical displacement (Van Roosendaal et al., 1994).

Water levels in the Trivoli Sandstone declined very rapidly some 37 to 43 m in the period from just before undermining until the subsidence tensile phase (Booth et al., 1994). Then, except for a 6 m rise in some piezometers during the compressional phase, no further recovery was observed in the sandstones during the subsequent three years of monitoring. Also, a 42-m-deep well into a shallow sandstone, located 300 m north of the panel, declined rapidly by about 22 m during mining in 1989 and recovered only about 1.5 m in winter 1994-1995.

Panel 5: Panel 5, approximately 1 km south of panel 1, was mined at a depth of about 91 m at the study site, which was undermined at New Year 1993. The glacial cover was 12 - 20 m thick and the Trivoli Sandstone was either sub-cropping at the bedrock surface or overlain by up to 2 m of shale beneath the glacial deposits. Further south, the sandstone becomes missing by erosion over panel 6, which was completed in July 1994.

The subsidence, strata deformation, and generally low permeabilities at panel 5 were similar to those at panel 1. The water levels in the sandstone piezometers (P51B-P53B) over the panel declined rapidly some 16-18 m during the period from just before undermining to the tensional phase of subsidence (Booth et al., 1997). The water level over the southern barrier pillar P54B) declined about 12 m. Figure 2 shows the sandstone piezometer hydrographs. There was no appreciable recovery of sandstone water levels over the panel in the three years after mining, but the water level in the piezometer over the barrier recovered rapidly by about 4 m a few weeks after mining.

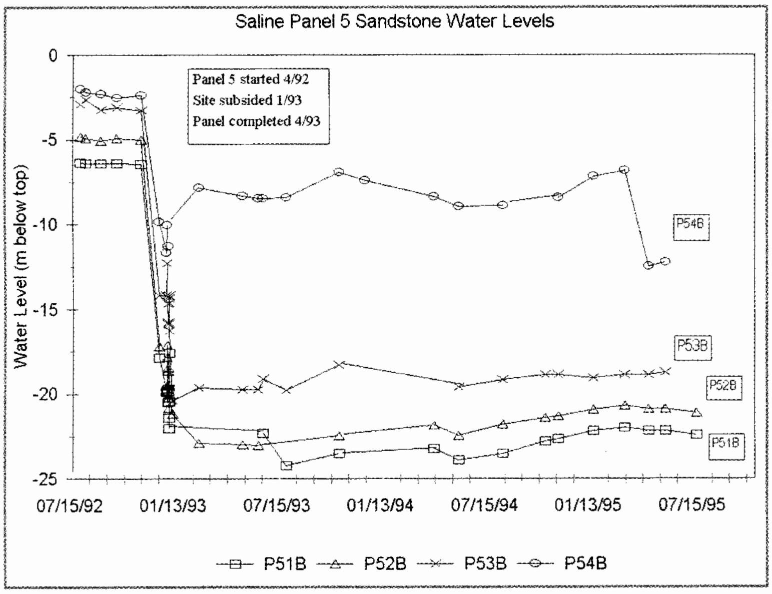

Figure 2. Hydrographs of Trivoli Sandstone piezometers over Panel 5, Saline Sit.

Figure 3 is a cross-section over panel 5 showing the piezometers, geology, panel position, pre-mining (November 1992) water levels in the sandstone (b-b) and deep drift (d-d), and post-mining (November 1994) water levels (b'-b' and d'-d'). The initial sandstone water level (b-b) was flat; the stable post-mining level (b'-b') is depressed over the panel, the aquifer being almost dewatered, but rises steeply to the partially recovered level at the barrier pillar. The potentiometric response in the lower drift (d-d, d'-d') varied across the panel. Over the center, the lower drift was poorly permeable clay till and its water levels fluctuated greatly during mining, then declined gradually by about 2-3 m. Over the southern barrier, the lower drift was sand and gravel, in which the water level fell rapidly during subsidence, concurrent with the head drop in the underlying sandstone. It then remained low at a level approximately equal to the head in the sandstone. The water level in the sandy till in the tension zone near the edge of the panel also declined substantially. These permeable drift units apparently lost water to the underlying sandstone, with which they were in good hydraulic continuity, and thus contributed to the local recovery of the sandstone in the barrier pillar area.

Discussion

The Jefferson and Saline County sites were similar in climate, topography, mined seam, and overall geological sequence. The initial potentiometric decline due to mine subsidence followed the same general pattern at both sites, though was more abrupt at the less transmissive Saline site. However, the potentiometric recovery in the shallow sandstone aquifers at the two sites was quite different. At Jefferson, recovery began soon after undermining and continued for over five years to an over-recovered level. No recovery occurred at either of the Saline panels during the post-mining monitoring periods, except locally over the southern barrier at panel 5 where the sandstone was recharged from overlying sand and gravel.

Recovery should be the normal response after a potentiometric level has been lowered by temporary stress. However, it can be prevented by any of three factors:

Continued loss of water from the aquifer

In areas of significant topographic relief such as the Appalachians, drainage can continue from upland aquifers through fractured aquitards to lower aquifers. However, this is not a factor in our low-relief setting.

Drainage can continue to the mine and deep caved zone. Generally, hydraulic separation is maintained between shallow aquifers and the mine and caved zone, provided that a sufficiently thick confining sequence is present. The Pennsylvanian coal-measure rocks in Illinois and Appalachia are dominated by shales which tend to retain their confining nature despite subsidence.

Situations in which the confining separation is inadequate could include highly permeable settings (such as the karst mining areas of China), localized buried bedrock valleys which bring sand and gravel aquifers close to the mine roof (as Cartwright and Hunt, 1976, reported for some wet mines in Illinois),

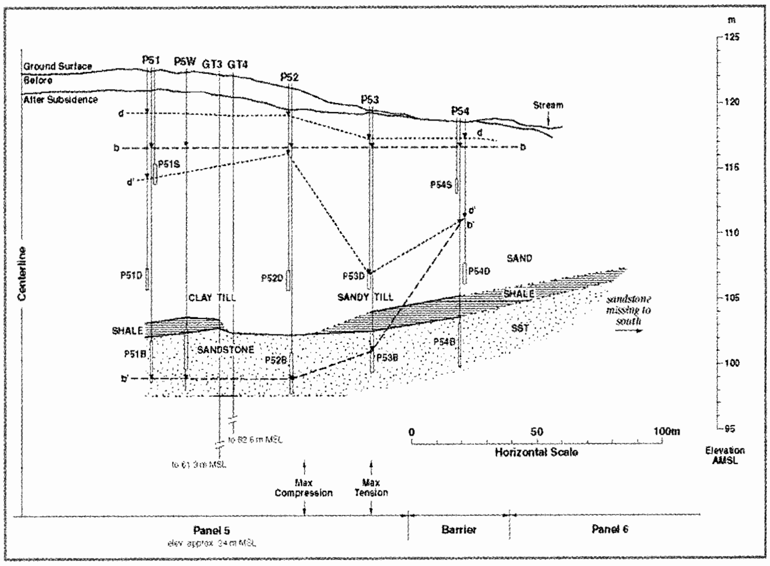

Figure 3. Cross-section over southern half of Saline panel 5 and barrier pillar, showing shallow strata, piezometer locations, and pre- and post-mining ground surface and water levels.

and very shallow longwall mining. Rauch (1989) suggested that a critical overburden thickness is about half the width of the panel. However, Matetic and Trevits (1991) reported complete recovery over shallow (61-91 m) longwall mining in Ohio, and Van Roosendaal et al. (1995) reported that confining separation was maintained and shallow water levels not depressed by a 106-m-deep longwall mine in Illinois.

In our case studies, inflow was not a general problem at either mine, and the confining layer separations were probably sufficient to prevent drainage from the aquifer to the mine or deep caved zone. At Jefferson, the sandstone aquifer was separated from the mine by about 168 m of bedrock, of which the lower 60 m were heavily fractured. At the Saline site, the shallower mining depth was offset by the limited extent (about 6 m) of the deep fractured zone above the mine. In both cases, geotechnical and packer tests showed that the confining zone above this contained isolated fractures and bedding separations that only locally increased permeability. At the Saline site the entire sequence, including the sandstone, remained tight, with isolated fractures into which injected water flowed only briefly. Thus, the differences in mining depth and possibility of continued drainage of water from the aquifer were probably not factors in the recovery process at the Illinois study sites.

The prevention of recharge water from flowing back through or into the aquifer

The transmissivity of the aquifer controls the rate at which recharge water can flow back into the affected areas of the aquifer. Considering the differences in thickness, initial permeability, and degree by which permeability was enhanced by subsidence, the Mt Carmel Sandstone at Jefferson was several hundred times more transmissive than the Trivoli Sandstone at the Saline site. This is probably the major cause of the differences in recovery between the sites. It is also reflected in the initial drawdown response to mining, which was more rapid and intense at the Saline site, more diffuse and gradual at the Jefferson site.

Additionally, the continued mining up-dip at Saline (compared to the end of mining at Jefferson) may have disrupted groundwater flow through the aquifer for part of the time. On the other hand, the active subsidence zone is a relatively small area, generally distant from the study sites, and for *most* of the time there was much more aquifer available for recharge, in all directions, than was being impacted by active mining. Furthermore, at panel 5, the continuing steep hydraulic gradient *within* the aquifer at the southern edge of the panel (Figure 3) suggests that the lack of recovery was a localized feature due to low transmissivity rather than to any influence of subsequent mining.

Lack of a source of recharge

At the Jefferson site, the sandstone was recharged both vertically from the overlying fractured shale and, more importantly, laterally through the aquifer from adjacent areas unaffected by mining. At the Saline site, there was no apparent vertical recharge from the thick, poorly permeable confining beds over the sandstone at panel 1 or from the till over the interior of panel 5, but there was local recharge from the sand and gravel over the barrier at the southern edge of panel 5. Laterally, the sandstone was missing south of panel 5, but again the steep hydraulic gradient near the edge of the panel suggests that the poor transmissivity is a more important factor.

CONCLUSIONS

Numerous studies show that a bedrock well directly over or close to a longwall mining panel typically experiences a drop in water level due to mine subsidence. The controls of this response include topographic setting and hydraulic properties of the aquifer. The depth of mining does not have a significant effect on shallow aquifers provided that a sufficiently thick confining zone maintains hydraulic separation between the aquifers and the deep caved zone and mine.

To predict whether a particular well or aquifer zone will exhibit significant potentiometric recovery from the depression after longwall mining, useful guidelines are:

- In areas of significant topographic relief, if the aquifer is on an upland and is separated from a deeper aquifer of lower head only by a thin, easily fractured confining unit, continued vertical drainage will tend to prevent recovery.
- If the well or aquifer is not adequately separated from the deep caved zone above the mine by a sufficiently thick confining unit, continued drainage to the deep zone will prevent significant recovery in a reasonable time.
- If the aquifer is thin and very poorly permeable, it will probably not recover in a reasonable time period; an indication of poor transmissivity is the suddenness and intensity of the initial potentiometric decline due to mining.
- The aquifer is less likely to recover if potential sources of recharge (e.g. overlying aquifers, lateral extent of the aquifer into unmined areas, location in a valley in an area of significant relief) are not available or are separated from the affected site by boundaries, continued mining, etc.

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