Environ Geol (2006) 49: 796–803
DOI 10.1007/s00254-006-0173-9

ORIGINAL ARTICLE

C.J. Booth

Groundwater as an environmental constraint of longwall coal mining

Received: 30 August 2005
Accepted: 12 December 2005
Published online: 25 February 2006
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C.J. Booth
Department of Geology and
Environmental Geosciences,
Northern Illinois University,
DeKalb, IL 60115, USA
E-mail: colin@geol.niu.edu
Tel.: +1-815-7537933
Fax: +1-815-7531945

Abstract Groundwater impacts are a common reason for opposition to longwall mining. Most impacts are due to subsidence-related fracturing. Although upper aquifers are protected from drainage to the mine by a confining zone, water levels decline due to fracture dilation, and drawdown expands outward a few hundred meters. Recovery of water levels is common.

Keywords Longwall mining · Subsidence · Well losses · Appalachia · Illinois USA

Introduction

Longwall and other high-extraction methods of underground coal mining cause rapid subsidence of the overlying strata and ground surface. Although groundwater inflows into the mine can be a technical problem, most of the environmental impacts on groundwater are caused indirectly by the subsidence. Mining companies are required to compensate landowners for loss of water and to provide alternative water supplies, but the loss of water supply is a serious problem to the people affected, regardless of compensation. These impacts are a common reason for opposition to longwall mining from residents and environmental groups; for the companies, they can become a significant obstacle in obtaining mining permits. This paper is intended to summarize, and cite findings and current concepts about the complex groundwater impact of longwall mining, for the benefit of hydrogeologists and engineers who may need to be consultants to either side, but who have little background in longwall hydrogeology. Case studies and concepts are mainly selected from Appalachia and Illinois, USA.

Current conflicts: is groundwater an environmental constraint for longwall mining?

Although longwall permit controversies are local issues, information about them is readily available on the Internet. While not scientifically reliable, such material is informative about the environmental concerns underlying public opposition to longwall mining. As with any environmentally controversial issue, the news media stress human-interest stories, especially of individuals versus corporations. Most internet-media reports concern opposition to longwall permit applications from environmental groups and residents, on the basis of anticipated or alleged impacts: structural damage or drainage problems caused by subsidence, loss of stream flow due to fractures in stream beds, loss of springs, and drying of wells and lowering of water levels. A few US examples, taken from many Internet reports, are:

1. Disputes over the loss of well water in a West Virginia community due to Arch Coal's Mingo Logan Mountaineer mine (Appalachian Focus Mining News 2000a, b; Charleston Gazette Online 2002). A

court ruling in 2000 allowed the company to continue undermining the community, provided that it replaces water supplies. Litigation was resolved in 2002 with a settlement of an undisclosed amount of money to 45 householders.

2. A controversy in Ohio concerns Dysart Woods, a 184-ha forest with approximately 22 ha of old-growth trees (Columbus AliveWireD 1997, 1998; The Post 1998; Anon 1998; Ohio Valley Coal Company 2003) The Ohio Valley Coal Company has applied for several permits to conduct longwall mining adjacent to the woods and contends that mining will not damage the trees. Opponents argue that mine-induced fracturing and subsidence will disrupt shallow drainage and deplete the groundwater supply in the forest. The arguments are both site specific (e.g., the supply of water to on-site seeps) and general (the extent to which longwall mining impacts forest growth).
3. A continuing controversy involves longwall mining in southwestern Pennsylvania. In 1994, Pennsylvania mining law was revised (PA Act 54) to give companies the right to longwall mine, and subside beneath homes and structures, but required them to provide appropriate remedial action, compensation, and alternative water supplies if wells lost water. The new law was strongly opposed by environmental organizations, on the basis of environmental justice and of damage to springs and livestock wells, loss of household wells, and the companies' use of plastic water-holding tanks as long-term alternative supplies (Pennsylvania Chapter Sierra Club 1997; Sierra Club 2001; Pittsburgh City Paper Online 2002). A 1999 study of 10 longwall and 74 room-and-pillar operations in southwestern Pennsylvania by the state's Department of Environmental Protection (1998) concluded that mine operators were replacing water supplies and fixing subsidence damage as required. DEP noted water loss or contamination in 28% of the properties (533, of which 310 were from longwall mining), and concluded that no damage occurred on two-thirds. Opponents criticized the data as deficient and argued that 72% of the actual responses indicated damage, with many cases unresolved (Pittsburgh Post-Gazette 1999). An example of disputes over a specific longwall mine in this area is Consol's Eighty-Four mine. Alleged damage included loss of well water to a flower nursery business in 1997–1998, and several other anecdotal reports of well failure (Pittsburgh Post-Gazette 2002) In 2001, the Commonwealth Court denied homeowners' objections to a longwall permit. A year later, a state court denied objections to the mine's extension and confirmed that longwall mining under property is legal despite damage (Democratic Underground 2001; Pittsburgh Post-Gazette 2001).

There is no doubt that longwall mining impacts well water levels, but state laws consider this as an acceptable consequence of mining provided that the mining companies remediate and compensate for damage. Groundwater will therefore be an issue in court each time there is opposition to a longwall permit or disputes over remediation and compensation. Hydrogeologists, whether as advocates or consultants, need to be familiar with the objective of science underlying these impacts.

The hydrogeological impact of longwall mining

Longwall mining involves the total extraction of large rectangular panels of coal, several kilometers long by 150–300 m wide, while keeping only the limited working face area of the mine supported. As the mine face advances, the unsupported roof behind collapses, and subsidence works up through the overlying strata to the ground surface, where a subsidence trough rapidly develops that outlines the mined-out panel. In contrast, room-and-pillar mining leaves pillars of coal to support the mine roof. High-extraction pillar removal results in similar subsidence as longwall mining.

In the USA, longwall mining and most groundwater case studies have been conducted since the 1970s in the Appalachian coalfield, a dissected plateau region of moderate to high relief (of order 10^2 m). The Pennsylvanian-age coal measures consist of coals, shales, siltstones, clays, thin limestones, and minor sandstone aquifers of moderate permeability and significant natural fracture influence. Since the 1980s, longwall mining and several case studies have also been conducted in the Illinois coalfield (midwestern USA), a region of low relief (of order 1–10^1 m), a glacial drift cover, and a generally less permeable groundwater system. Longwall mining is also conducted elsewhere in the USA (e.g., Utah).

A conceptual model of the hydrogeological effects of longwall coal mining has gradually been developed from numerous case studies (Booth 2002). All underground mines potentially drain groundwater from aquifers with which they are in contact, but the subsidence and strata movement due to longwall mining also affect the groundwater system independently from mine drainage. Fracturing and bedding separation cause changes in fracture porosity and permeability, and thus in hydraulic gradients and groundwater levels (Hill and Price 1983; Walker 1988; Matetic and Trevits 1991, 1992). Above a mined panel, the overburden strata form three major zones of deformational and hydrologic response (Singh and Kendorski 1981; Peng 1986; Rauch 1989; Booth 2002; Younger et al. 2002; Fig. 1):

I. A lower, severely fractured zone of greatly increased permeability drains directly into the mine. Its height is variously described as a third to a half the width of the panel, or between 20 and 60 times the extraction thickness. Wells that bottom in this zone lose their water.

II. An intermediate compressional zone that subsides coherently with little extensive fracturing. It typically forms in a shale interval and maintains overall low permeability, confining characteristics between the mine and shallow aquifer system.

III. The uppermost zone consists of shallow strata subject to extensional stress and fracturing. Aquifers are affected by in situ fracturing but not necessarily by drainage into the mine, from which they are hydraulically separated by zone II. Wells over the mine in this zone commonly have significant but temporary water-level declines, often followed by recovery.

The intermediate low-permeability zone was first clearly noted by Singh and Kendorski (1981), and is now well understood (Tieman and Rauch 1987; Booth 2002) as typically preventing drainage from shallow aquifers to the mine. The minimum thickness needed to maintain the hydraulic separation will vary depending on lithology, structure, and topography. Minimum separations between the mine and well bottoms in Appalachia are typically described in the 90–150 m range (Rauch 1989; Elsworth and Liu 1995). However, in an Illinois study (Van Roosendaal et al. 1995), an overburden sequence of shales and glacial clay prevented the loss of water from shallow sand aquifers to a longwall mine only 60 m deep.

As a site is undermined, the shallow strata first experience tensional stresses and shear deformation, tension cracks open at the ground surface, the ground subsides rapidly, and bedding separations open. Fracture porosity and permeability increase. In the interior of the subsidence trough, a subsequent compressional stress phase causes fractures to partially close, and permeability and porosity to decrease back somewhat. However, the outer margins of the trough experience only the tensional phase and thus retain higher permeabilities. The magnitudes of the fracture-induced permeability changes in the upper zone also vary depending on the interaction of the stress regime with site hydrogeological characteristics such as topography and lithology. Increases of one or two orders of magnitude of permeability, transmissivity, or specific capacities are most commonly reported (e.g., Johnson and Owili-Eger 1987; Matetic and Trevits 1991, 1992; Johnson 1992) for Appalachia and also from our studies in Illinois (Booth et al. 1997).

Illinois studies

Northern Illinois University (NIU) and the Illinois State Geological Survey (ISGS) studied the hydrology and subsidence over two active longwall mines in southern Illinois, USA, from 1988 to 1995. Since details of the investigations have been extensively published (Mehnert et al. 1994; Van Roosendaal et al. 1994; Booth et al. 1997, 1998, 2000; Booth 1999; Booth and Bertsch 1999), only summary information is given here.

The Illinois coalfield strata comprise Pennsylvanian-age coal measures dominated by low-permeability shales

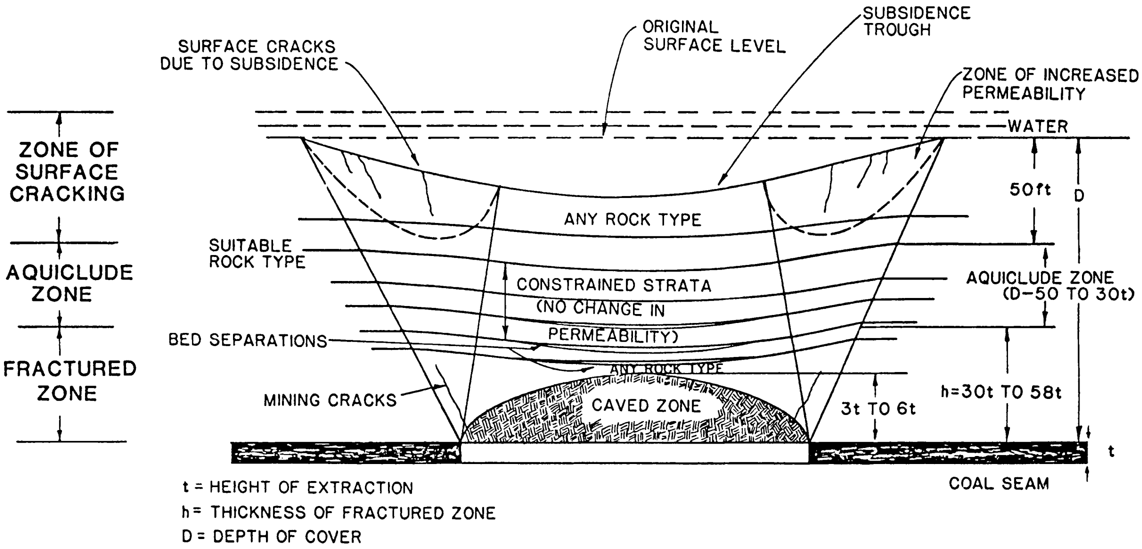
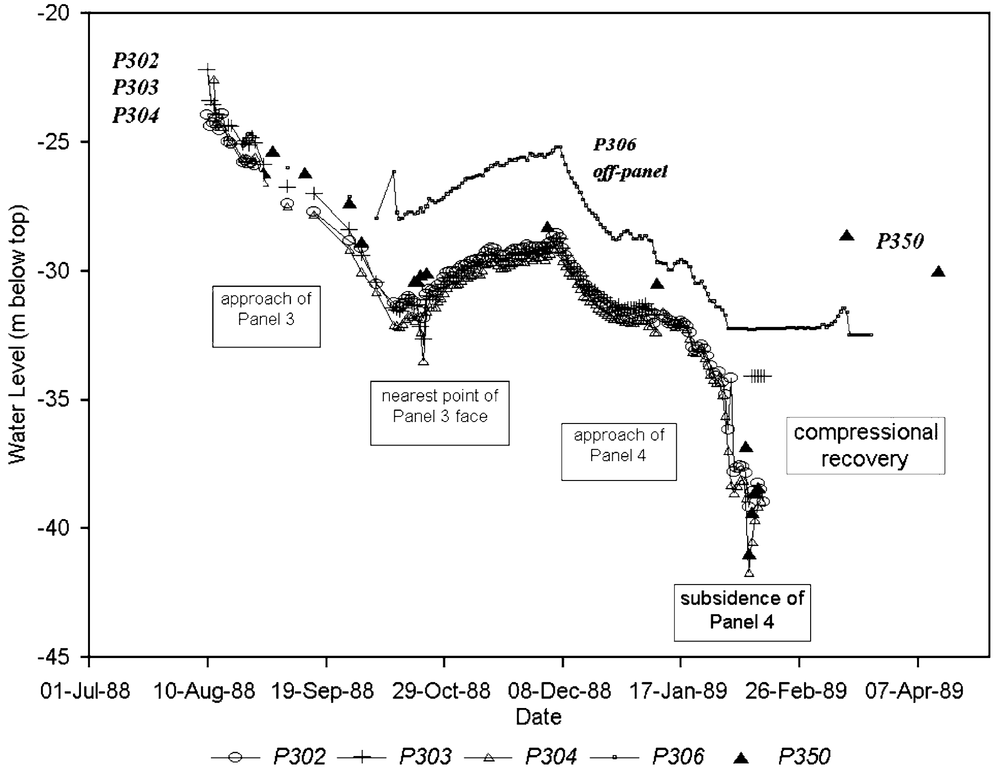


Fig. 1 Strain and permeability zones above a longwall panel (from Singh and Kendorski 1981)

Fig. 2 Decline in potentiometric levels in the Mt. Carmel Sandstone over longwall panel 4, Jefferson County site (from Booth et al. 1997)



and overlain by Pleistocene glacial deposits. Topographic relief is low, groundwater flow systems are slow, and brackish to saline water may be encountered at depths of 50 m or less. Fresh groundwater resources are mostly limited to minor sand-and-gravel units within the till and to shallow, poorly transmissive sandstones. Most public supplies use surface-water reservoirs, but shallow groundwater is important for rural residential and farm livestock supplies. At both sites studied, the overburden strata consisted of shales, siltstones, thin limestones, sandstones, coals and clays, overlain by till with discontinuous sand-and-gravel units, lake deposits at one site, and a cover of loess. Local relief is about 15 m. Studies were started before the mining of particular panels and continued for several years afterwards. The ISGS monitored vertical subsidence, horizontal ground strains, and subsurface strains (Mehnert et al. 1994; Van Roosendaal et al. 1994). Hydrological studies included potentiometric monitoring of piezometers and wells drilled on site and of existing residential and farm wells, and sampling for geochemical analysis. Hydraulic properties were determined using packer, slug, and pumping tests.

Jefferson County site

Four longwall panels, each about 183 m wide by over 1,530 m long were mined in a coal seam 3 m thick at a depth of 222 m. Our studies focused on final panel 4 and the Mt Carmel Sandstone, an aquifer 23–25 m thick, 174 m above the mine, and 24 m below ground level (BGL), overlain by shale and glacial drift. Ground subsidence rapidly reached 2 m along the panel centerline and was accompanied by considerable strata fracturing, particularly shear fractures along the tensional margins of the subsidence trough and vertical bedding separation in the central trough area (Mehnert et al. 1994; Booth et al. 1998). The sandstone permeabilities (initially 10^{-7} m/s) increased by one order of magnitude in the inner subsidence trough and two orders along the margin. Water levels in the sandstone declined (Fig. 2) as the mine face approached, reached a minimum of about 43 m BGL (unconfined) at maximum tension during undermining, and then partially recovered during the compressional stress phase (Booth et al. 1998; Booth 1999).

Levels eventually recovered (Fig. 3) to about 12 m BGL by 4 years after mining. These sandstone water levels thus displayed a response to fracture dilation in the subsidence area, the transmitted drawdown beyond it, and recovery by compression and recharge. In contrast, the only responses in drift water-table wells were brief fluctuations during active ground movements and a slight adjustment to the new topography.

Significant changes occurred in the groundwater chemistry of the sandstone aquifer (Mehnert et al. 1994; Booth and Bertsch 1999). The pre-mining water was

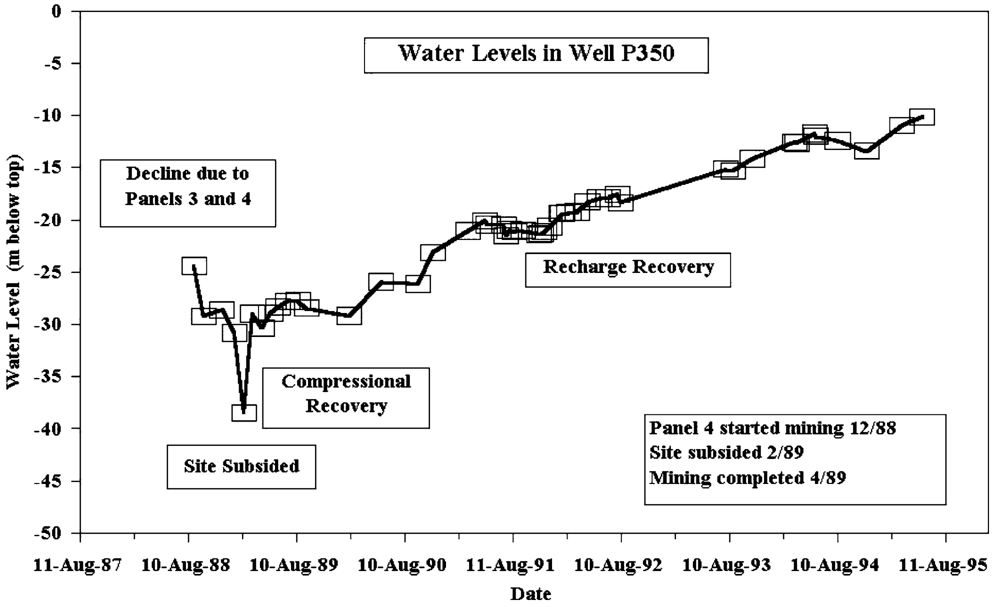


Fig. 3 Recovery of potentiometric levels in Mt. Carmel Sandstone, Jefferson County site, following longwall mining (from Booth 1999)

fresh to slightly brackish (TDS 900–1,200 mg/l), and sodium-bicarbonate dominant, with sulfate less than 200 mg/l. During post-mining recovery, the TDS rose to more than 2,600 mg/l, and sulfate to over 1,200 mg/l. We attribute the deterioration in quality to increased leakage from the overlying shale and to the mobilization of sulfate from sulfides on the sandstone, by water flowing back through the aquifer after it became unconfined.

Saline County site

Six adjacent longwall panels were mined in a 2-m-thick coal seam overlain by shale-dominated bedrock with several thin to discontinuous poorly permeable (10^{-8} m/s) sandstones. The glacial drift cover was between 12 and 27 m thick. The bedrock dips at about 23 m/km, and our studies concentrated on down-dip panel #1 (204 m wide, 122 m deep), and up-dip panel #5 (287 m wide, 97 m deep). The centerline subsidence for both was around 1.4 m, and maximum horizontal tensional and compression strains were located about 15 and 41 m from the panel's edges (Van Roosendaal et al. 1994; Booth et al. 2000). Sandstone permeabilities over both panels were low (10^{-8}–10^{-7} m/s) and only minimally increased due to subsidence.

Water levels in the sandstone over panel #1 fell rapidly at undermining, from about 12 m BGL to 49–55 m (unconfined condition), and did not significantly recover after mining. The water level in a sandstone well 300 m north of the panel declined from 11 to 33.5 m but in 4 years did not recover. Shallow drift wells at the same distance had no response to mining. At panel #5, the sandstone was only 20 m deep and sub-cropped at the bedrock surface. Despite the shallower setting, the sandstone water levels again fell rapidly with undermining, to an almost-dewatered condition. The only recovery was on the barrier edge of the panel where the sandstone was recharged from overlying sand and gravel, a localized unit not present over the center where the drift consisted of clay till.

Areas of influence

The lateral limit of the influence of mining on groundwater is often compared to the "angle of draw" which defines the limit of subsidence movement relative to the edge of the panel. Younger et al. (2002) note that this angle is in the range 20–40° and that the comparable angle of groundwater influence is not restricted by the angle of draw but is usually within 40° except in steep terrain. However, measures, such as angle of groundwater influence or ratios to depths of the mine, have no real meaning except as empirical guidelines for a particular hydrogeologic setting. The angle of draw defines only the edge of the strata movements causing the primary hydrologic response to fracture changes; the extent of groundwater influence beyond the subsidence zone is controlled by the transmitted drawdown—i.e., by the hydraulic properties of the aquifer. Since most coalfield aquifers have relatively low transmissivities, the effects reach only a few 100 m despite the steep head drop over the mine, except where extended by fracture zones; and they may extend only tens of meters where the transmissivities are very low.

Thus, various studies in the Appalachian coalfield show apparent angles of groundwater influence that vary widely: e.g., 16–24° in the upper overburden zone and 32° in the lower zone (Cifelli and Rauch 1986); 38–60° to the limits of influence at 177–387 m (Moebs and Barton 1985); and distances to the initial potentiometric response of 120–180 m (approximately the thickness of the overburden, an angle of about 45°; Walker 1988). Tieman and Rauch (1987) found that dewatering of wells separated by at least 150 m above the mine at a site in Pennsylvania extended a distance of about 300 m at an "angle of dewatering influence" of about 42°. Hutcheson et al. (2000) observed that water-level responses in Kentucky were related to the complex flow system rather than to an angle of hydrologic influence, and were transmitted as far out as 442 m in conductive strata.

Recovery of water levels after mining

The recovery of water levels in wells impacted by longwall mining is an important environmental consideration, since it is more costly and difficult to replace a permanent loss than to provide temporary supplies. Water levels in the subsidence zone commonly soon recover slightly due to post-subsidence compressional stresses. Water levels should also recover as water flows back into the temporary potentiometric depression created by the subsidence fracture effects. However, this recovery depends on connection to sources of recharge and on the ability of the aquifer to transmit water back into the affected area. At our study sites in Illinois, full recovery after mining occurred at the site with a moderately transmissive aquifer, but almost none at the site where the sandstone had very low transmissivity and restricted lateral pathways to sources of recharge (Booth et al. 1998, 2000; Booth 1999).

Permanent changes in groundwater flow may be caused by the increases in permeability, because of gradient changes or leakage through fractured aquitards. Most sites will exhibit permanent head losses somewhere. However, in many cases, water levels and stream flows recover at least partially within a few months after mining (Tieman and Rauch 1987; Walker 1988; Matetic and Trevits 1992). Long-term recovery is hard to predict, as several Appalachian studies show. In one study (Cifelli and Rauch 1986), only one of 19 water supplies (30–100 m deep, probably in the lower fractured zone) above total extraction mining had any significant recovery, whereas in another (Matetic and Trevits 1991), only one well (at the center of a panel) out of ten shallow wells did not have some recovery. Werner and Hempel (1992) considered that recovery was likely in wells below the regional water table but not in perched aquifers below which the aquitard had been fractured; however, case studies are reported in which recovery typically occurred within a few months, even in upland situations over fractured aquitards which presumably healed (Johnson and Owili-Eger 1987). In a study of 174 domestic water wells near longwall mines in the Pittsburgh seam (Leavitt and Gibbens 1992), 64% returned to service without the need for remedial action; valley wells were less affected by mining than upland wells, a finding also in other studies (Younger et al 2002). Rauch (1989) concluded that dewatered shallow wells above the mine recovered rapidly (hours to weeks), wells on steep hillsides took months, hillside springs had poor to no recovery, and that where the overburden thickness is less than half the panel width, wells did not significantly recover within years, except near a stream. Longwall-impacted spring supplies similarly recovered better near stream channels (Tieman and Rauch 1987).

Conclusions

Groundwater impacts are an environmental constraint of longwall mining, whether considered as a problem for residents of mined areas or as a problem for companies in permit applications. Longwall mining affects overlying aquifers by several different mechanisms. Groundwater levels may be lowered because of drainage to the mine, but normally this is prevented by an intermediate low-permeability zone, and is a problem only for deeper wells that penetrate the lower fractured zone, or if natural fracture zones are present. However, in situ fracturing causes impacts independently of either mine drainage or, above a certain level, depth to the mine. Sudden increases in fracture porosity cause large, transient head drops in confined bedrock aquifers. A secondary drawdown effect is then transmitted through the aquifer outwards from the advancing subsidence zone. Increased permeabilities cause head drops up-gradient, increased discharges down-gradient, and, in higher relief areas, head drops due to leakage through fractured aquitards. Although the subsidence zone is described by the angle of draw, the lateral extent of the secondary drawdown is controlled by the transmissivity of the aquifer, and typically extends only a few hundred meters. Ratios of depths to the mine or angles of groundwater influence are only empirical guides for particular hydrogeologic settings.

Wells that penetrate the lower fractured zone generally do not recover. Otherwise, a rapid small compressional recovery is common in subsided areas; longer-term recharge-based recovery may take weeks to years depending on the transmissivity of the aquifer, connection to sources of recharge, continued loss of water through fractured aquitards, or continued mining.

Acknowledgments Contributors to the Illinois research were ISGS personnel RA Bauer, BB Mehnert, PJ Demaris, DJ Van Roosendaal, and J Kelleher, and NIU graduate assistants ED Spande, CT Pattee, JD Miller, AM Curtiss, and LP Bertsch. The research was funded by the Illinois Department of Energy and Natural Resources (1988–1992), and by the Office of Surface Mining Reclamation and Enforcement of the US Department of the Interior (1991–1995: Contract Agreement #GR 196171). This support does not constitute an endorsement by either DENR or OSM of any views expressed in this article, which are solely those of the author.

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