Horizontal Hydraulic Conductivity Estimates for Intact Coal Barriers Between Closed Underground Mines

KURT J. McCOY

JOSEPH J. DONOVAN

Department of Geology and Geography, West Virginia University, Morgantown, WV 26506

BRUCE R. LEAVITT

Consulting Hydrogeologist, 2776 S-Bridge Rd., Washington, PA 15301

Key Terms: ***Groundwater Hydrology, Hydraulic Conductivity, Mining Hydrogeology, Coal Mine Barriers***

ABSTRACT

Unmined blocks of coal, called barriers, separate and restrict horizontal leakage between adjacent bituminous coal mines. Understanding the leakage rate across such barriers is important in planning mine closure and strongly affects recharge calculations for postmining flooding. This study presents upper-limit estimates for hydraulic conductivity (K) of intact barriers in two closed mines at moderate depth (75–300 m, or 250–980 ft) in the Pittsburgh coal basin. The estimates are based on pumping rates from these mines for the years ranging from 1992 to 2000. The two mines do not approach the outcrop and are sufficiently deep that vertical infiltration is thought to be negligible. Similarly, there are no saturated zones on the pumped mines' side of shared barriers with other mines, and therefore pumping is the only outflow. Virtually all of the pumping is attributed to leakage across or over the top of barriers shared with upgradient flooded mines. The length of shared barriers totals 24 km (15 mi) for the two mines, and the barriers range in thickness from 15 to 50 m (50–160 ft). K values calculated independently for each of the 9 years of the pumping record ranged from 0.037 m/d to 0.18 m/d (0.12 ft/d to 0.59 ft/d) using an isotropic model of barrier flow. Using an anisotropic model for differential K in the face cleat (K_f) and butt cleat (K_b) directions, results range from 0.074 to 0.34 m/d (0.24 to 1.1 ft/d) for K_f and from 0.022 to 0.099 m/d (0.072 to 0.32 ft/d) for K_b.

INTRODUCTION

Postmining hydrology of underground mines has been a concern for both industry and regulatory agencies because of the potential for uncontrolled mine-water discharges following mine closure. One phenomenon associated with mine-water budgets that can be of critical importance in postmining hydrology is flow between adjacent mines that are partially or completely filled with water (flooded). To date, only sparse literature providing data for quantification of barrier leakage between mines is available. As a result, mine barriers are commonly modeled using rule-of-thumb estimates of hydraulic conductivity (K), which are embedded in experience and regulatory practice (The Pennsylvania Bituminous Coal Mine Act Sections 291 and 294, 25 Pa. Code Sections 89.35–89.36, 89.54). The purpose of this article is to provide new methods and estimates of barrier K from the bituminous-rank Pittsburgh coal district of northern West Virginia, as well as to place these results within the context of barrier K estimates reported elsewhere in the literature. The results assume minimal influence of vertical infiltration and represent upper-limit estimates of K (actual K values would be less based on the amount of vertical infiltration that actually occurs).

Deep underground-mine aquifers in the Pittsburgh coal (Pennsylvanian) of West Virginia and Pennsylvania result from postmining resaturation of voids and associated fractures produced by coal extraction. These fractures permit groundwater from rocks above the coal to flow into the mine workings, forming saturated conditions updip of unmined coal, including both internal barriers (i.e., islands of coal within mined areas) and perimeter barriers. As flooding continues, small "pools" merge into a single main "pool" saturated region (Donovan and Fletcher, 1999). When adjacent flooded mine "pools" show independent water-level relationships, then the barriers separating them may be considered intact. Intact barriers substantially impede horizontal flow and serve as aquitards with vertical geometry. Fracturing above longwall-mined coal commonly extends up to 60 times the thickness of the coal itself (Singh and Kendorski, 1981). In contrast to longwall-mined coal, supported room-and-

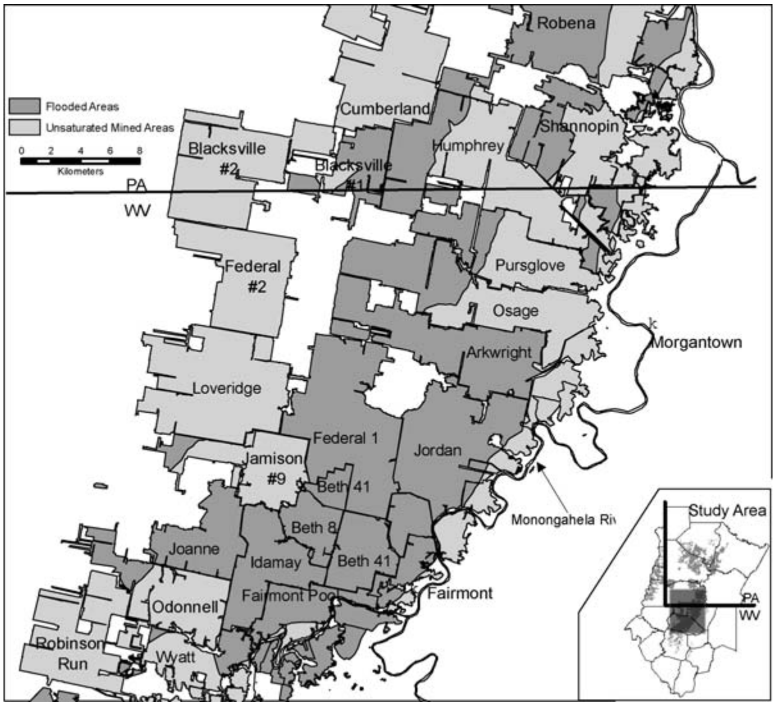

Figure 1. Underground mined areas in the Pittsburgh coal near Fairmont, WV. Year 2000 flooding status shown in dark gray.

pillar mined coal and advancing of mains leaves pillars intact and is therefore thought to retard subsidence and roof collapse (Booth, 1986). Similarly, for the coal barrier to serve as an aquitard, the extent of fracturing above the unmined coal, where compressional load-bearing stresses are likely high, must itself be minimal.

''Nonintact'' barriers, on the other hand, are those that had at one time been breached by an entry or borehole between mines. Many such entries were sealed during mining with block walls, cement, or bulkheads, in which case the degree of leakage generally depends on the effectiveness of such seals. Leavitt (1999) noted that barriers between mines closed prior to the 1950s are likely to be nonintact.

Leavitt (1999) discusses intact barriers for the closed Robena mine adjacent to the active Humphrey mine in the Pittsburgh coal in northern West Virginia (Figure 1). At a location about 200 m (660 ft) below land surface in 1995, the head in Robena was 118 m (387 ft) above the mine floor along its 85-m (279-ft)–wide barrier with Humphrey, a water pressure of 11.9 kg/cm^2 (169 psi). Only minor leakage across the barrier was observed despite the high pressure. This pressure difference indicates that the hydraulic conductivity of this barrier was quite low, although without knowing the magnitude of seepage, it is unclear how low it is.

The rate of leakage across intact barriers is determined by the horizontal hydraulic conductivity (K_h) of the coal itself, the width of the barrier, and, perhaps, the orientation of the barrier with respect to systematic jointing (butt and face cleat) of the coal. Cleat orientation tends to follow regional structure. Face cleat or the predominant joint set forms perpendicular to regional folding, and the butt cleat or secondary joint set generally forms parallel to folding. Major controls on K_h include the degree, density, and horizontal continuity of fracturing in undisturbed coal as well as any opening of fractures induced by pressure release on the outside of the barrier.

PURPOSE

The purposes of this investigation are to present a technique to estimate intact barrier hydraulic conductivity using field data from underground mine water levels and pumpage and to present results of this analysis for a specific mining district. The area chosen for this analysis is in the Pittsburgh coal in northern West Virginia. Use of field data at large scale, however, is complicated by the difficulty in distinguishing barrier leakage from the vertical infiltration that occurs in most mines. The Jamison #9 and Odonnell mines in the Pittsburgh coal basin (Figure 1) are thought to have sufficiently low vertical infiltration and sufficiently high barrier leakage that reasonable upper-limit estimates of K_h can be made. Because the mines are relatively deep and have no outcrop exposure, the water budgets of these two mines are thought to be dominated by barrier leakage inflow and pumping outflow. Also, both these mines and surrounding mines are near steady state with respect to water levels and flooding. Therefore, the setting is ideal to estimate K_h of intact barrier sections at a field scale incorporating thousands of meters of barrier length. No such estimate at this large spatial scale is known to have been reported in the literature.

PREVIOUS INVESTIGATIONS

Hydraulic conductivity values discussed in this article were obtained from 16 previous investigations of mine sites in bituminous, sub-bituminous, and lignite coal-producing regions of the country. In West Virginia, Pennsylvania, and northeastern Ohio, aquifer tests were conducted by Aljoe and Hawkins (1992), Hobba (1991), Schubert (1980), and Miller and Thompson (1974). Additional aquifer test results have been presented by Minns and others (1995), Harlow and LeCain (1993), and Harper and Olyphant (1993) in Kentucky, Virginia, and Indiana, respectively. Others have evaluated the hydraulic properties of eastern coal seams using numerical and laboratory simulations (Dabbous et al., 1974; Dames and Moore, 1981; Luo et al., 2001; McCoy, 2002; and McCoy et al., 2004).

Hydraulic properties of western coal seams are reported by McCord and others (1992) in Colorado and New Mexico and by Rehm and others (1978, 1980), Chadwick (1981), Stoner (1981), and Stone and Snoeberger (1977) in low-rank beds of the Fort Union Formation in North Dakota, Montana, and Wyoming.

Several authors have described the hydraulic conductivity of coal as anisotropic; this conductivity is ascribed to the difference in permeability along the face cleat or cleavage of the coal compared to the butt cleat. Hobba (1991) found that anisotropic ratios ranged from 2 to 15, with a median of 3.4, in the Upper Freeport coal of West Virginia. Schubert's (1980) summary of several studies indicated a range of 2 to 10 in West Virginia coals. Stoner (1981), Vogwill (1979), Stone and Snoeberger (1977), and Erickson (1970) found anisotropic ratios of western coals to differ by a factor of 2.5 and 2.9, 2.4, 1.8, and 4.8, respectively.

STUDY AREA

The Pittsburgh coal basin trends north–northeast in a large syncline, 130 × 65 km (80 × 40 mi), in parts of southwest Pennsylvania, northwest West Virginia, and southeast Ohio. The coal averages about 1.5 to 2 m (5 to 7 ft) in thickness and has been extensively mined in southwestern Pennsylvania and northwestern West Virginia for over 150 years. Much of this early mining in West Virginia occurred near surface around the town of Fairmont, which is located approximately 25 km (15 mi) south of the Pennsylvania state line in Marion County. Figure 1 shows many of the larger mines in Marion County and Monongalia County, WV, and Greene County, PA. Mining progressed from the outcrop in a down-dip direction, such that younger, larger mines are found at greater depths to the west. Two such mines, Jamison #9 mine and Odonnell mine, are surrounded by older fully flooded mines yet are maintained dry for adjacent mine operations.

The closed Jamison #9 mine occurs at the western limit of mining on the east side of the coal basin (Figure 1). It lies in the vicinity of McClellan, WV, at depths of 120 m (390 ft) up-dip along valleys to 300 m (980 ft) down-dip along uplands. It shares its northern barrier with the active (dry) Loveridge mine (Figure 2). To keep water from seeping across this barrier into Loveridge, Jamison #9 is pumped at the Llewellyn shaft to maintain the water level below 145 m (470 ft). The wetted portion of the barrier is about 1.2 km (0.75 mi) of the 8.2 km (5.1 mi) along the Loveridge–Jamison #9 barrier section. On the up-dip side, Jamison #9 shares barriers with Federal #1, Beth 8, Beth 41, Idamay, and Joanne mines, all five of which are fully flooded and at substantially higher hydraulic head than the elevation of the Jamison #9 barrier. Thus, five mines contribute barrier leakage to Jamison #9, virtually all of which is pumped out at Llewellyn shaft, as the leakage into Loveridge mine, by engineering design, is negligibly small.

The closed Odonnell mine is about 12 km (7.5 mi) south of Jamison #9 mine, in an essentially identical hydrogeological setting (Figure 3). It lies in the vicinity of Wyatt, WV, at depths of 75 m (250 ft) up-dip along valleys to 240 m (790 ft) down-dip along uplands. It shares a portion of its southern barrier with the active (dry) Robinson Run mine and is pumped at Thorne and Whetstone shafts to maintain the water level below 180 m (590 ft). Odonnell shares "wet" barriers with Joanne, Idamay, and Williams, all of which contribute barrier leakage to it. Coal extraction methods used in the individual mines are shown in Table 1.

METHODOLOGY

Under the assumptions that the only inflows are from barrier leakage across "n" barrier segments (i.e., vertical infiltration is negligible) and that the only outflow is to pumping, then a mass balance quantifying upper-limit estimates of barrier leakage with Darcy's Law can be invoked, thus:

$$Q_{pump} = \sum_{i=1}^{n} K_h b L_i \frac{\Delta h_i}{w_i} \tag{1}$$

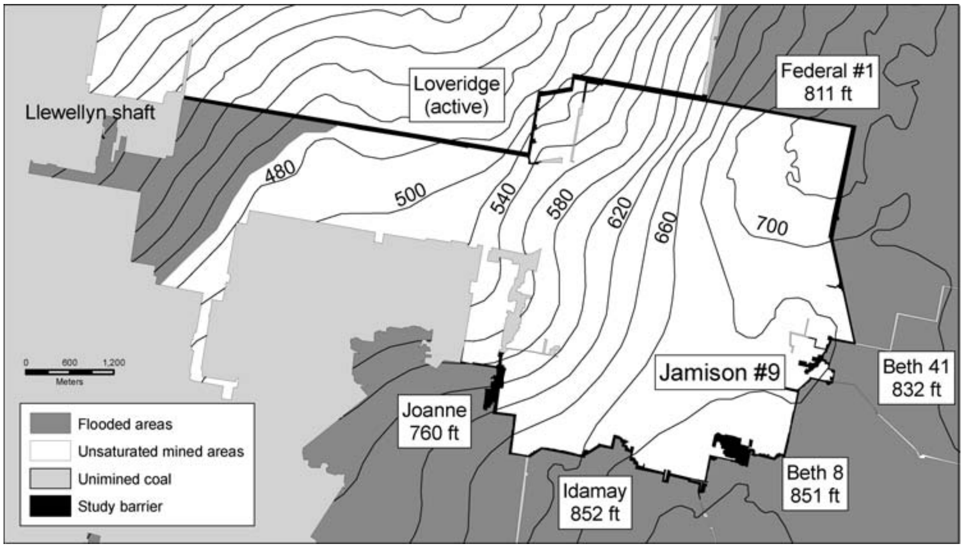

Figure 2. Structure contours of the bottom of the Pittsburgh coal in Jamison #9 and surrounding mines with year 2000 flooding status indicated in dark gray. Individual mine water levels listed are mean pool elevations for year 2000. 1.000 ft = 0.3048 m.

where Q_{pump} = pumping discharge [L^3/T]; K_h = horizontal hydraulic conductivity [L/T]; b = mine-aquifer thickness or height of seepage face under confined conditions [L]; L_i = barrier segment length [L]; Δh_i = head difference across barrier [L]; and w_i = barrier width [L].

The head difference may be estimated using hydraulic head elevation in the ''wet'' mine and average elevation of the top of the coal along the barrier in the ''dry'' mine. The water level in the pumped mines implies saturation of the full seam thickness and confined flow across the entire width of the barrier. Barriers separating the Jamison #9 and Odonnell mines from adjacent mines are thought to be fully pressurized, as 87 percent of the barrier segments maintain head differences in excess of

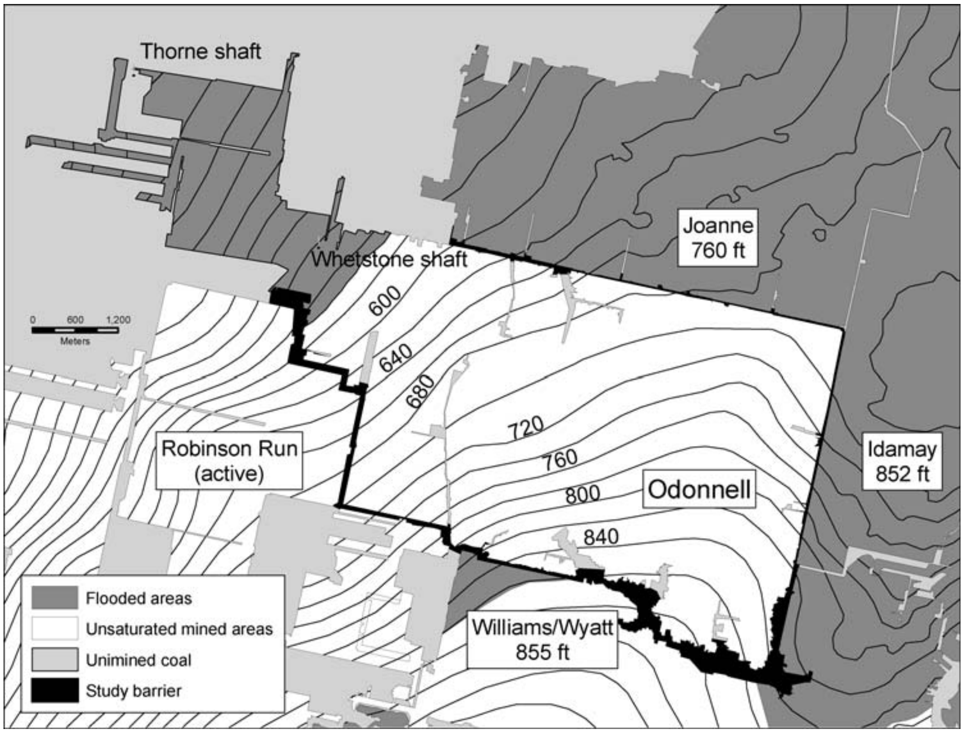

Figure 3. Structure contours of the bottom of the Pittsburgh coal in Odonnell and surrounding mines with year 2000 flooding status indicated in dark gray. Individual mine water levels listed are mean pool elevations for year 2000. 1.000 ft = 0.3048 m.

Table 1. *Mining method for individual mines in the study area.*

Mine	Mining Method
Jamison	R&P
Odonnell	R&P, LW
Federal #1	R&P, LW
Beth 8	R&P
Beth 41	R&P
Idamay	R&P
Joanne	R&P
Williams	R&P
Loveridge	LW
Robinson Run	LW

R&P = room and pillar mining; LW = longwall mining.

27 m (90 ft). However, one barrier segment of 60 m (190 ft) in width and 1,700 m (5,600 ft) in length separating Odonnell and the adjacent Williams mine maintains only a 2.7-m (8.8-ft) head difference above the top of the coal on the dry mine side, the lowest head difference of all barrier segments. In this case, a partially unconfined condition may prevail in the barrier provided there is sufficient head loss across the barrier that the height of the downgradient seepage face is less than the mine-aquifer thickness (b). However, there is no known subsurface evidence for a partially saturated downgradient seepage face, and for this reason, a fully confined Darcy's Law formulation, rather than a Dupuit formulation, is favored to describe flow between the two mines across the barrier.

Water levels were obtained from industry and regulatory data repositories. To estimate missing water levels, values in some cases were interpolated over periods ranging from 1 to 6 years (Figure 4). Flooding rates were estimated for each mine from existing data and established head relationships between adjacent mines. A complete record of water-level data was available for only one mine (Idamay). However, none of the mines show abrupt variation or strong seasonal influences, allowing water levels to be interpreted from sparse readings. Discharges at each respective pumping well were assumed to be equal to reported treatment volumes at associated mine-water treatment facilities. Rates were also assumed to be constant throughout the year. Annual pumping discharges were obtained from industry reports stored at the Consol Energy field office in Osage, WV, for Llewellyn shaft (Jamison #9) and the Whetstone and Thorne wells (Odonnell) (Table 2).

Zero vertical infiltration (roof leakage) is implicitly assumed in Eq. 1 under the assumption that at the depths of cover for these two mines, infiltration is negligible. As a result, the K_h values derived from this analysis must be considered maximum values. The actual K values would be lower given the addition of vertical infiltration estimates to the mass balance in Eq. 1. In the absence of data, upper-limit K_h results are presented, as any such estimate of vertical infiltration would be arbitrary.

In this study, Eq. 1 is evaluated by defining the mine aquifer thickness (b) as the thickness of the coal (a regional average of 2 m, or 6.5 ft). However, it is conceivable that horizontal flow could extend upward to above the coal barrier itself (Figure 5). In any case, all horizontal flow—both that going through the coal and that leaking above it—is captured by the mine pumps and is included in the discharge Q_{pump}. Therefore, treating

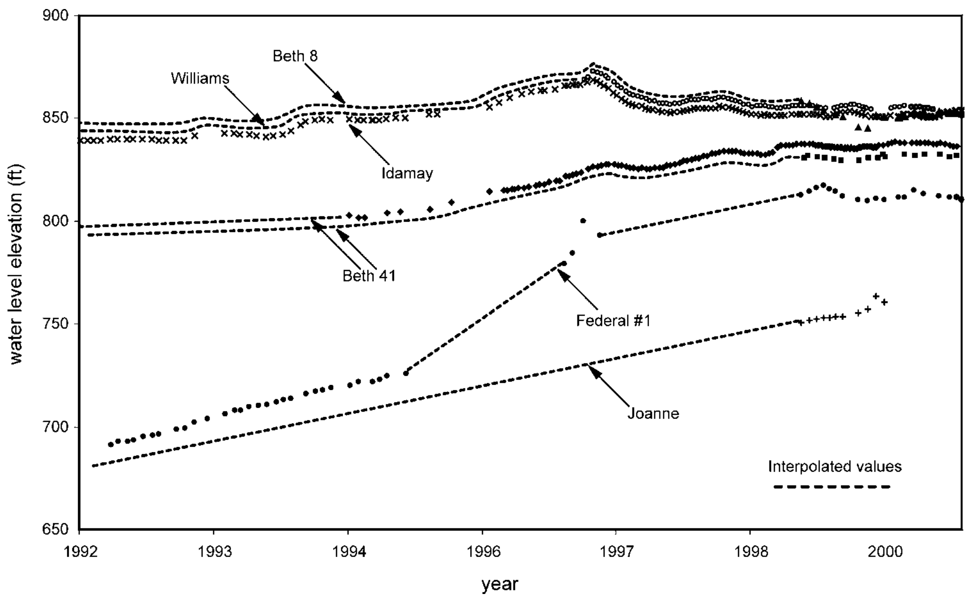

Figure 4. Hydrograph showing observed and interpolated data from mines adjacent to Jamison #9 and Odonnell. 1.000 ft = 0.3048 m.

Table 2. *Reported yearly pump discharge from Jamison and Odonnell in $m^3/yr \times 10^6$ ($m^3/yr = 35.3$ ft^3/yr).*

Mine	1992	1993	1994	1995	1996	1997	1998	1999	2000
Jamison	0.681	0.390	0.916	1.253	0.969	0.768	0.715	1.185	1.348
Odonnell	0.613	0.651	0.587	0.538	0.534	0.428	0.575	0.609	0.269

flow as occurring through the coal only is a simplifying assumption. Should flow occur above the coal as well as through it, the "effective height" of the barrier-flow zone would be increased and the resulting K estimates proportionally decreased. Fluxes resulting from K values by either convention would be identical, provided they are applied consistently with the convention of calculation. In this article, flow is treated as if horizontal leakage occurs through the coal only.

Invocation of Eq. 1 implicitly assumes that coal-barrier properties are homogeneous at the scale of this study. For application of Eq. 1, wetted barriers were discretized into segments that are uniform in width. K_h was then adjusted to fit the summed barrier-calculated leakage to the pumping discharge for each mine on a year-by-year basis.

Jamison #9 was divided into 24 wetted barrier segments. The barriers ranged in width from 5 m (16 ft) to 120 m (390 ft), with hydraulic head differences up to 59 m (194 ft). Odonnell was divided into 15 segments ranging from 15 m (49 ft) to 180 m (590 ft) in width, with head differences up to 40 m (131 ft). Water budgets for both mines were computed for each calendar year from 1992 to 2000, years for which sufficient pumping data were available.

RESULTS

Estimation of K_h Using an Isotropic Model

Values of K_h were calculated directly from Eq. 1 (isotropic model) for each of the 9 years of record for each mine (Table 3). K_h in the Jamison #9 models ranged from 0.053 m/d (0.17 ft/d) (1993) to 0.14 m/d (0.46 ft/d) (1995), with a median of 0.093 m/d (0.31 ft/d). K_h in the Odonnell models ranged from 0.037 m/d (0.12 ft/d) (2000) to 0.18 m/d (0.59 ft/d) (1992 and 1993), with a median of 0.090 m/d (0.30 ft/d). The results agree to ±40 percent between Jamison #9 and Odonnell except for years 1992, 1993, and 2000 in Odonnell. The cause for these discrepancies is unknown. The average of all 18 annual values is 0.099 m/d (0.32 ft/d).

Estimation of K_h Using an Anisotropic Model

For the same flow data, an anisotropic model was applied to see if the resulting K values deviate significantly from the hydraulic conductivities obtained for the isotropic model. To do this, the local value of the angle between face cleat and barrier orientation was measured for each of the barrier segments. The regional value reported by Stoner (1983) of N 70°W from Greene County, PA, was used as an estimate of face cleat direction. Hobba (1991) found similar values of N 69.5°W and N 66.5°W nearby in the Upper Freeport coal. For each barrier segment, all acute face cleat-barrier angles, drawn at contour line-barrier intersections, were averaged to a single angle. The variation for individual segments was generally ±40 percent or

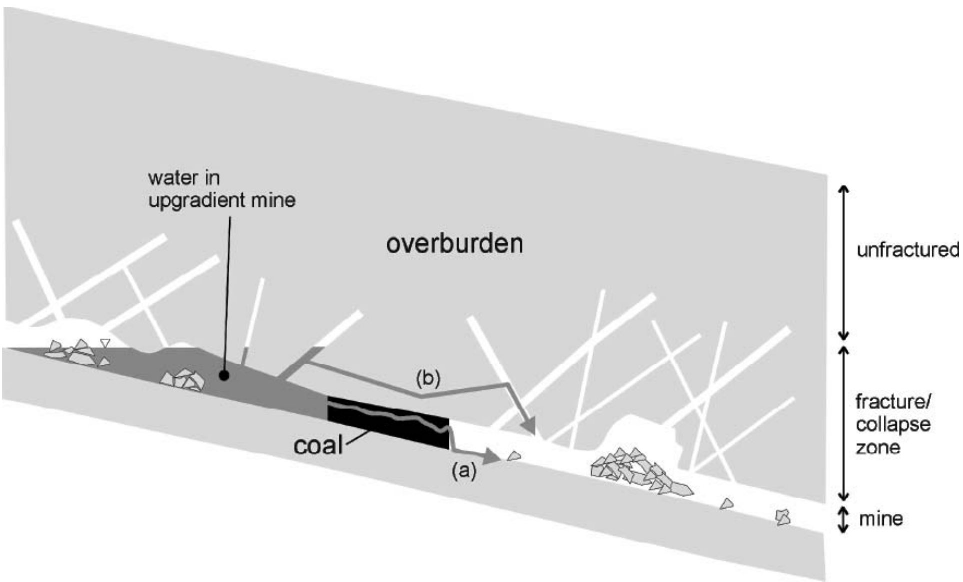

Figure 5. Conceptual models of leakage from a saturated upgradient mine: (a) through an intact barrier or (b) circumventing an intact barrier. Assuming equal rates of leakage, hydraulic conductivity in (a) is much higher as a result of smaller saturated thickness.

Table 3. *Calculated results of barrier K_h, K_f, and K_b using Eq. 1 and Eq. 3 (m/d = 3.3 ft/d).*

Mine	Calendar Year	K_h (m/d)	K_f (m/d)	K_b (m/d)
Jamison	2000	0.106	0.144	0.042
Jamison	1999	0.093	0.126	0.037
Jamison	1998	0.060	0.082	0.024
Jamison	1997	0.066	0.091	0.027
Jamison	1996	0.089	0.125	0.037
Jamison	1995	0.142	0.204	0.060
Jamison	1994	0.112	0.164	0.048
Jamison	1993	0.053	0.078	0.023
Jamison	1992	0.102	0.154	0.045
Odonnell	2000	0.037	0.074	0.022
Odonnell	1999	0.087	0.174	0.051
Odonnell	1998	0.088	0.175	0.052
Odonnell	1997	0.067	0.132	0.039
Odonnell	1996	0.090	0.176	0.052
Odonnell	1995	0.110	0.213	0.063
Odonnell	1994	0.136	0.263	0.077
Odonnell	1993	0.177	0.337	0.099
Odonnell	1992	0.158	0.337	0.099
	Mean	0.099	0.169	0.050
	Median	0.092	0.159	0.047

K_h = horizontal hydraulic conductivity; K_f = face cleat; K_b = butt cleat.

less. The azimuth of the butt cleat was taken as 90° to the estimated face cleat (Stoner, 1983; Hobba, 1991).

Using these angles, a conceptual model of the cleats' intersection with the barrier was developed to estimate the effective length of each "cleat" across each barrier (Figure 6), thus:

$$\lambda_i = \frac{w_i}{\sin \theta_i} \quad \text{and}$$
$$\kappa_i = \frac{w_i}{\cos \theta_i}$$

where λ_i = the length of face cleat across the barrier [L]; κ_i = the length of butt cleat across the barrier [L]; w_i = barrier width [L]; and θ_i = the average acute angle between face cleat and barrier.

For anisotropic media, Eq. 1 becomes:

$$Q_{pump} = \sum_{i=1}^{n} \left(\frac{K_f}{\lambda_i} + \frac{K_f}{(K_f/K_b)\kappa_i} \right) bL_i \Delta h_i \qquad (3)$$

According to Eq. 2, barrier orientation lends to shorter flow paths along the butt cleat direction for these two mines; θ_i approaching zero indicates near-perpendicular orientation of the butt cleat to the long dimension of the barrier. These two specific mines tend to be dominated in their conductance by the butt cleat, which indicates that the lower value of K_b is the limiting factor in controlling flow across these barriers.

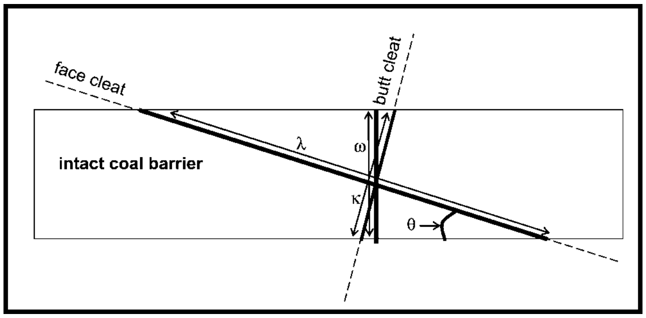

Figure 6. Planar schematic (map-view) diagram showing intersection between coal face/butt cleats and a mine barrier. Measurements are indicated by arrows.

Eq. 3 was applied to Jamison #9 and Odonnell mines from 1992 through 2000 to describe flow along two separate flow paths (face and butt cleat), each with a respective K value (K_f and K_b) and continuous-flow path length determined using Eq. 2. The results from Eq. 3 are maximum values of directional K given an anisotropy (K_f/K_b) of 3.4, the ratio obtained by Hobba (1991) in a nearby location within the Upper Freeport coal of West Virginia. K values were determined by iterative adjustment of K_f while maintaining Hobba's (1991) ratio until the discharge from both flow paths summed to the known discharge Q_{pump}.

Fitted K_f and K_b ranged from 0.078 m/d (0.26 ft/d) and 0.023 m/d (0.075 ft/d) (1993), respectively, to 0.20 m/d (0.66 ft/d) and 0.060 m/d (0.20 ft/d) (1995), respectively, in the Jamison #9 model (Table 3). The average values for the Jamison #9 model were 0.13 m/d (0.43 ft/d) (K_f) and 0.038 m/d (0.12 ft/d) (K_b). K_f and K_b ranged from 0.074 m/d (0.24 ft/d) and 0.022 m/d (0.072 ft/d) (2000), respectively, to 0.34 m/d (1.12 ft/d) and 0.099 m/d (0.33 ft/d) (1992 and 1993), respectively, in the Odonnell model. The average values for the Odonnell model were 0.21 m/d (0.69 ft/d) (K_f) and 0.062 m/d (0.20 ft/d) (K_b). These large values are similar to previously published values of K_h, K_f, and K_b from bituminous and sub-bituminous coal seams.

Methods Comparison

Values of coal hydraulic conductivity calculated from this study and cited from other studies in the literature are summarized in Table 4 and plotted as minimum, maximum, and median values in Figure 7. These 40 values from bituminous to lignite seams encompass a range of seven orders of magnitude, attributed to differing test methodology, sample scale, and heterogeneity of fracture spacing within coal aquifers. However, approximately 70 percent of the literature-cited values fall within a two–order of magnitude range, from 0.01 to 1 m/d (0.03 to 3.0 ft/d), including all but two values from surface-mined coals in the Powder River Basin.

Table 4. *A list of literature-cited values of coal hydraulic conductivity (m/d = 3.3 ft/d).*

	Date	K_{min} (m/d)	K_{max} (m/d)	K_{median} (m/d)	Seam	Rank*	Formation/Group	Depth (m)	Method	Where
Isotropic K										
McCoy and others	2004	0.03	0.15	0.09	Pittsburgh	b	Monongahela Group	300–500	Modeling	WV
Luo and others	2001		0.07					400	Modeling	
Minns and others	1995	8.80E–05	0.004	2.63E–04	Fireclay	b	Breathitt Formation	100–300	Packer tests	KY
Harper and Olyphant	1993	0.06	3.5	1.5	Mariah Hill	b	Mansfield Formation	23–30	Slug tests	IN
Harlow and Lecain	1993	3.40E–05	2	0.01		b	Early to Middle Pennsylvanian**	0–300	Packer tests	VA
Aljoe and Hawkins	1992			0.11		b			Well tests	WV, PA
McCord and others	1992	1.0	0.01			b	Fruitland Formation	750	Heat flux data	CO, NM
Hobba	1991	3.3	4.4		Upper Freeport	b	Allegheny Group	20	Well tests	WV
Dames and Moore	1981	0.31	1.5					100–200	Modeling	
Rehm and others	1980			0.86		l, sb	Fort Union Group		Aquifer tests	ND, WY, MT
Rehm and others	1978			0.35		l	Fort Union Group		Aquifer tests	ND
Dabbous and others	1974	8.70E–04	0.01		Pittsburgh	b	Monongahela Group		Laboratory	PA
Miller and Thompson	1974	0.22	0.96	0.3	Upper Freeport, Lower Kittaning	b	Allegheny Group	10–30	Packer tests	PA
Anisotropic K										
McCoy and others	2004	0.02–0.09	0.07–0.30		Pittsburgh	b	Monongahela Group	300–500	Modeling	WV
Chadwick	1981	0.3	2.5		D1 upper seam	l, sb	Fort Union Group		Well tests	MT
Stoner	1981	0.23–0.34	0.49–0.73		Sawyer A, Anderson	l, sb	Fort Union Group	40	Well tests	MT, WY
Vogwill	1979	0.37	0.86						Well tests	Alberta
Stone and Snoeberger	1977	0.15	0.27			l, sb	Wasatch Formation		Well tests	WY

*b = bituminous; sb = sub-bituminous; l = lignite.
**Lee, Pocahontas, New River, Norton, and Wise Formations, Gladeville Sandstone.

Analytical solutions to well tests produced coal hydraulic conductivity values from 0.06 m/d to 4.4 m/d (0.19 ft/d to 14 ft/d). The upper range of these values (>1.0 m/d, or 3.0 ft/d) reflects results from relatively shallow depths (20–30 m, or 65–100 ft) or across several aquifer zones (Chadwick, 1981; Hobba, 1991; Harper and Olyphant, 1993). Median values from well-instrumented sites in shallow western coals range across only one order of magnitude, although Rehm and others (1980) report possible ranges of 10,000 to 0.001 m/d (30,000 to 0.003 ft/d) in North Dakota, Montana, Wyoming, and Alberta. Lignite seams of the western United States display substantial heterogeneity and less continuous horizontal fracture (cleat) (Stoner, 1981), but low values of hydraulic conductivity are also commonly reported in bituminous seams of the eastern United States.

Harlow and LeCain (1993) used 3-m (10-ft) packer tests in Late Mississippian to Pennsylvanian bituminous coals to determine hydraulic properties. Variation in test interval depth (0–100 m, or 0–300 ft) and geologic formation likely explains the range of three to four orders of magnitude in their results, although 50 percent of their tests fall within two orders of magnitude. Packer test results by Stoner (1981) and Miller and Thompson (1974) correspond to those of Harlow and LeCain (1993) at shallow depths (10–35 m, or 30–100 ft). In deeper coals, Minns and others (1995) confirmed that high confining pressures appear to limit fracture conductivity. In fact, packer testing of small intervals at depth may sample predominantly unfractured material or, at least, much less conductive fractures. Similarly, the chances of intersecting conductive fractures in laboratory analysis of core samples are less than those in larger-scale field experiments and therefore result in generally lower hydraulic conductivity values for lab results (Dabbous et al., 1974).

Numerical simulations of barrier seepage and stability by Luo and others (2001) resulted in results comparable to those presented by the current study. Both investigations calculated values that fall within the middle

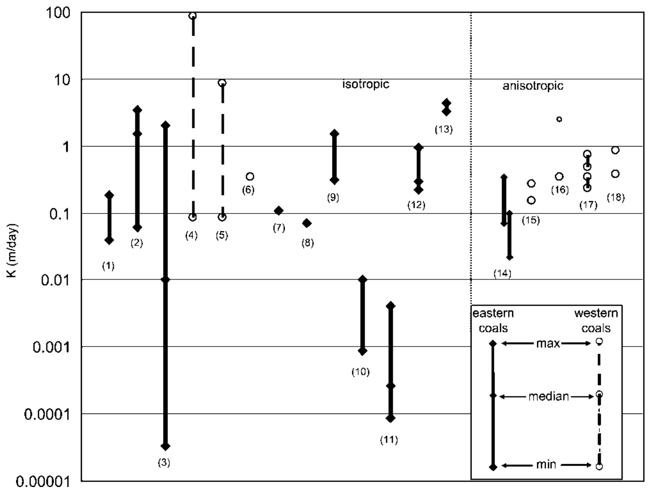

Figure 7. Comparison of hydraulic conductivity values from the literature and present study. Key: [1,14]present study; [2]Harper and Olyphant (1993); [3]Harlow and LeCain (1993); [4]McCord and others (1992); [5]Rehm and others (1980); [6]Rehm and others (1978); [7]Aljoe and Hawkins (1992); [8]Luo and others (2001); [9]Dames and Moore (1981); [10]Dabbous and others (1974); [11]Minns and others (1995); [12]Miller and Thompson (1974); [13]Hobba (1991); [15]Stone and Snoeberger (1977); [16]Chadwick (1981); [17]Stoner (1981); [18]Vogwill (1979).

70th percentile range of literature-cited values. Slightly higher values were used by Dames and Moore (1981) to simulate outcrop barriers of Appalachian coal mines.

In an evaluation of heat-flux data in the high-rank Fruitland Formation coals of Colorado and New Mexico, McCord and others (1992) found values to range from 10^{-1} to 10^{2} m/d (0.3–300 ft/d). Despite the depth and rank of these coals (~750 m, or 2,500 ft), groundwater flow using heat-flux data was found to be several orders of magnitude greater than values determined from well tests or numerical models in similar rank coals.

CONCLUSIONS

Flows across barriers in the Jamison #9 and Odonnell mines in northern West Virginia were analyzed in a series of large-scale field experiments using both isotropic and anisotropic models based on a fully saturated continuum Darcian approach. Assumptions of homogeneity and Darcian flow were made given the large scale of analysis (many kilometers). K was assumed to be independent of barrier width and spatially uniform. Cleat angles and ratio of anisotropy were obtained from the literature. Pumping data from closed mine operations were annualized, and one spatially uniform average barrier K value per year per mine was estimated along long sections of barriers in the Pittsburgh coal, using mine-pumping rates under prevailing hydraulic-head conditions. Hydraulic conductivity estimates for the two mines ranged from 0.074 to 0.34 m/d (0.24 to 1.1 ft/d) along face cleat and 0.022 to 0.099 m/d (0.072 to 0.32 ft/d) along butt cleat, based on an anisotropy ratio of 3.4. The isotropic K estimates ranged from 0.037 to 0.18 m/d (0.12 to 0.59 ft/d). Both models assumed that vertical infiltration into all mines down-dip of the leaky barrier was zero. As a result, the calculated K values are all upper-limit estimates. The actual K values would be somewhat lower, to the extent that vertical infiltration actually occurred into these mines.

The annual isotropic results were consistent with each other with the exception of 3 years (1992, 1993, and 2000). It is possible that pumping records for these years underestimated withdrawals. Excluding these years, the mean isotropic K is 0.095 m/d (0.31 ft/d) for both mines, with a standard error of 0.026 ft/d.

Commonly a failure to appreciate heterogeneity in a hydrogeologic investigation may lead to erroneous results. However, in this case, comparisons between these large-scale experimental results and those collected at smaller scale indicate consistency in hydraulic conductivity between scales of investigation. The values obtained here are slightly lower than those obtained in multiple and single-well tests of western sub-bituminous or lignitic coals. Packer tests, well tests, numerical models, and laboratory results from eastern coals all fall within a one–order of magnitude range about the mean of the barrier-test results. These observations all indicate that the range of horizontal K values for barrier leakage observed at scales of multiple kilometers in this investigation is consistent with smaller field-scale results reported in the literature. It is not, however, consistent with laboratory tests.

These results have specific limitations. The coal grade is all bituminous, and the depth of occurrence of >96 percent of the length of these barriers is from 75 to 300 m (250–980 ft). In addition, the continuum model assumes that all flow is horizontal and occurs through the coal barrier itself. A portion of the flow may occur through overburden rocks above the coal, as the mine aquifer extends to several times the thickness of the coal above the top of the coal seam (Singh and Kendorski, 1981). However, the consistency of these results with well- and packer-test estimates argues that estimates of K derived from flow solely through the coal barrier itself are realistic, albeit upper limit by convention as a result of the conservative estimate of aquifer thickness and assumption of zero vertical infiltration. Most importantly, these estimates are derived from large-scale observations more similar in scale to fluxes associated with barrier leakage in the field than the experimental conditions of other K testing methods reported to date.

ACKNOWLEDGMENTS

The authors appreciate the data contributions of Eric Perry of the U.S. Office of Surface Mining, Pittsburgh, PA. Access to mine map archives was provided by the West Virginia Geologic and Economic Survey, Morgantown, WV, and West Virginia Department of Environmental Protection, Philippi, WV. We also appreciate the thorough reviews of Colin Booth and two anonymous individuals.

This publication was supported by the U.S. Department of Energy, National Energy Technology Laboratory, Award Number DE-AM26-99FT40463. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

REFERENCES

Aljoe, W. W. and Hawkins, J. W., 1992, Application of aquifer testing in surface and underground mines: *Groundwater Management,* Vol. 13, pp. 541–555.

Booth, C. J., 1986, Strat-movement concepts and the hydrogeological impact of underground coal mining: *Groundwater,* Vol. 24, No. 4, pp. 507–515.

Chadwick, R. A., 1981, Anisotropic hydraulic conductivity in coal and clinker, East Decker mine site, Montana: *Geological Society America Abstracts Programs,* Vol. 13, No. 4, p. 193.

Dabbous, M. K.; Reznik, A. A.; Taber, J. J.; and Fulton, P. F., 1974, The permeability of coal to gas and water: *Society Petroleum Engineers Journal,* Vol. 14, No. 6, pp. 556–565.

Dames and Moore, 1981, *Outcrop Barrier Design Guidelines for Appalachian Coal Mines:* Contract report 395069 prepared for the U.S. Bureau of Mines, Pittsburgh Research Center, 166 p.

Donovan, J. J. and Fletcher, J., 1999, *Hydrogeological and Geochemical Response to Mine Flooding in the Pittsburgh Coal Basin, Southern Monongahela River Basin:* Project WV-132, Report to the U.S. Environmental Protection Agency, 47 p.

Erickson, K., 1970, *Surficial Lineaments and their Structural Implications in the Williston Basin, ND*: Unpublished M.S. Thesis, University of North Dakota, 69 p.

Harlow, G. E., Jr. and LeCain, G. D., 1993, *Hydraulic Characteristics of, and Groundwater Flow in, Coal Bearing Rocks of Southwestern Virginia:* U.S. Geological Survey Water Supply Report 2388, 36 p.

Harper, D., and Olyphant, G. A., 1993, Statistical evaluation of hydrologic conditions in the vicinity of abandoned underground coal mines around Cannelsburg, Indiana: *Journal Hydrology,* Vol. 146, No. 1–4, pp. 49–71.

Hobba, W. A., Jr., 1991, *Relation of Fracture Systems to Transmissivity of Coal and Overburden Aquifers in Preston County, West Virginia:* U.S. Geological Survey Water Resources Investigation Report 89-4137, 24 p.

Leavitt, B. R., 1999, Mine flooding and barrier pillar hydrology in the Pittsburgh basin. In *Proceedings 16th Annual International Pittsburgh Coal Conference*, Pittsburgh, PA, 11 p.

Luo, Y., Peng, S. S., and Zhang, Y. Q., 2001, Simulation of Water Seepage Through and Stability of Coal Mine Barrier Pillars: Society for Mining, Metallurgy, and Exploration, Inc., Denver, CO, preprint number 01-131, 6 p.

McCord, J., Reiter, M., and Phillips, F. M., 1992, Heat-flow data suggest large groundwater fluxes through Fruitland coals of the northern San Juan Basin, Colorado-New Mexico: *Geology,* Vol. 20, No. 5, pp. 419–422.

McCoy, K. J., 2002, *Estimation of Vertical Infiltration into Deep Pittsburgh Coal Mines of WV-PA: A Fluid Mass Balance Approach*: Unpublished M.S. Thesis, West Virginia University, 151 p.

McCoy, K. J., Donovan, J. J.; and Leavitt, B., 2004, Estimation of hydraulic conductivity of coal mine barriers, Pittsburgh coal, northern WV, 1992–2000. In *Proceedings of the 2004 Joint Conference of the American Society of Mining and Reclamation and the West Virginia Surface Mine Drainage Task Force Symposium*: ASMR, Lexington, KY, pp. 1218–1226.

Miller, J. T. and Thompson, D. R., 1974, Seepage and mine barrier width. In *Papers of the Symposium on Coal Mine Drainage Research*, No. 5: National Coal Association, Washington, DC, pp. 103–127.

Minns, S. A., Kipp, J. A., Carey, D. I., Dinger, J., and Sendlein, L. V. A., 1995, *Effects of Longwall Mining on Hydrogeology, Leslie County, Kentucky, Part 1, Premining Conditions:* Kentucky Geological Survey Report of Investigations 9, Series XI, 44 p.

Rehm, B. W., Groenewold, G. H., and Moran, S. R., 1978, The hydraulic conductivity of lignite and associated geological materials and strip mine spoils, western North Dakota: *Geological Society of America Abstracts with Programs,* Vol. 10, No. 7, p. 477.

Rehm, B. W., Groenewold, G. H., and Morin, K. A., 1980, Hydraulic properties of coal and related materials, northern Great Plains: *Groundwater,* Vol. 18, No. 6, pp. 551–561.

Schubert, J. P., 1980, Fracture-flow of groundwater in coal-bearing strata. In *Proceedings of the Symposium on Surface Mining Hydrology, Sedimentology, and Reclamation:* University of Kentucky, pp. 61–73.

Singh, M. M. and Kendorski, F. S., 1981, Strata disturbance prediction for mining beneath surface water and waste impoundments. In *Proceedings of the 1st Conference on Ground Control in Mining*: West Virginia University, Morgantown, WV, p. 76–89.

Stone, R. and Snoeberger, D. F., 1977, Cleat orientation and areal hydraulic anisotropy of a Wyoming coal aquifer: *Groundwater,* Vol. 15, No. 6, pp. 434–438.

Stoner, J. D., 1981, Horizontal anisotropy determined by pumping in two Powder River Basin coal aquifers, Montana: *Groundwater,* Vol. 19, No. 1, pp. 34–40.

Stoner, J. D., 1983, Probable hydrologic effects of subsurface mining: *Groundwater Monitoring Review,* Vol. 3, No. 1, pp. 128–137.

Vogwill, R. I. J., 1979, Hydrogeological testing associated with underground coal gasification: *Canadian Geotechnical Journal,* Vol. 16, pp. 59–68.