ESTIMATION OF HYDRAULIC CONDUCTIVITY OF COAL MINE BARRIERS, PITTSBURGH COAL, NORTHERN WEST VIRGINIA, 1992-2000[1]

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Abstract. Unmined coal barriers separate adjacent coal mines and restrict horizontal leakage between mines. Understanding the leakage rate across such barriers is important in planning mine closure and strongly affects recharge calculations for post-mining flooding. This study presents maximum estimates for intact (non-compromised) barrier hydraulic conductivity (K) in two closed mines at moderate depth (100-350 meters) in the Pittsburgh coal basin. The estimates are based on pumping rates from these mines 1992-2000 associated with leakage across common barriers from upgradient flooded mines. Both the pumped mines were maintained nearly dry, and so had dry seepage faces downdip from flooded mines, allowing accurate estimates of hydraulic gradient. The two mines do not approach the outcrop and are sufficiently deep that vertical infiltration is thought to be negligible. Similarly, there are no wetted barriers facing on other mines, and therefore pumping is the only discharge. The length of barriers totals 24 kilometers for the two mines, generally ranging in thickness from 15 to 50 m, and so the K test was large-scale. These test conditions are ideally suited to K estimation. K values from the test ranged from 0.03 m/d to 0.15 m/d using an isotropic model, and 0.05 to 0.27 (face cleat K_f) and from 0.03 to 0.15 m/d (butt cleat K_b) using an anisotropic model.

Additional Key Words: mining hydrogeology, coal barriers, aquitards

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Introduction

Because head differences across barriers are common in areas of flooded mines, it is necessary to quantify the role of perimeter barriers in limiting groundwater flow between mines. "Intact barriers" are those which represent continuous, uninterrupted thicknesses of coal between mines. The degree of leakage across intact barriers is determined by horizontal hydraulic conductivity (K_h) of the coal itself, thickness of the barrier, head differences, and orientation of the barrier with respect to fracturing (butt and face cleat) of the coal. 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, into the voids adjacent to the barrier.

Hydraulic head and discharge data from two pumped underground coal mines and adjacent active and inactive mines in northern West Virginia has been used to estimate hydraulic conductivity of mine barriers in the Pittsburgh coal with both isotropic and anisotropic modeling.

Barrier Pillar Hydrology

Barrier leakage is thought to be greatest in rate at shallower depths, where fracture density is greater and barriers are usually thinner than at depth (Lewis and Burgy, 1964; Schubert, 1980; Donovan and Fletcher, 1999). Stoner and others (1987) hypothesized that hydraulic conductivity of strata decreases by an order of magnitude with every 30 m increase in mine depth.

Estimating the role of flow through intact perimeter barriers is challenging. Previous studies reporting K_h of coal seams include Harper and Olyphant's (1993) average of 2.5×10^{-2} m/day for the Buckeye mine in the Mariah Hill coal member of the Mansfield formation near Cannelburg, Indiana. Harlow and LeCain (1993) found a range of 3.4×10^{-5} m/day to 2.0 m/day (median 0.5 m/day) using 3 m packer tests in Late Mississippian to Pennsylvanian coals in southwest Virginia (Lee, Pocahontas, New River, Norton, Wise, and Harlan formations). McCord et al., (1992) found a range of 10^{-1} to 10^{-3} m/day using heat flux data in high-rank, Late Cretaceous Fruitland formation coals of Colorado and New Mexico. In North Dakota, Wyoming, Montana, and Alberta, Rehm et al., (1980) calculated an average of 2.8×10^{-3} m/day. Rehm et al., (1978) estimated K at 5.8×10^{-3} m/day in low-rank Paleocene lignite beds of western North Dakota. Leavitt (1993) estimated a minimum K of Pittsburgh coal barrier pillars in Fairmont, West Virginia as 0.1 m/day. Luo et al., (2001) simulated barrier seepage flow using a value of 0.075 m/day.

The hydraulic properties of coal are described by some authors as anisotropic. Stone and Snoeberger (1977) ascribed directional hydraulic conductivity, in Wasatch Formation coal aquifers in Wyoming, to differences in permeability along the face (dip direction) cleat or cleavage of the coal compared to the butt (strike direction) cleat. They found face cleat consistently more permeable than butt cleat in the Fort Union formation of Wyoming and Montana. Using well pumping tests, K in the face cleat direction (K_f) was calculated to be 0.27 m/day, compared to 0.15 for butt cleat (K_b). This indicated an apparent anisotropy of 1.8. Chadwick (1981) reported an average of 2.5 m/day (K_f) and 0.34 m/day (K_b) using multiple-well pump tests in the D_1 Upper coal seam of southeast Montana for an anisotropy of 7.4. Schubert (1980) reported a range of anisotropy from 2 to 10 in coal deposits of West Virginia.

Methods

Two West Virginia mines in the Pittsburgh coal, Jamison and Odonnell, were identified as ideal locations for estimation of K_h due to mapped geometry of their barriers, availability of pumping records, and known hydrologic status of adjacent mines. For both mines, all water losses are due to pumping and primarily represent inflow from adjacent mine barriers, as vertical inflow is thought to be negligible. There are no barrier outflows.

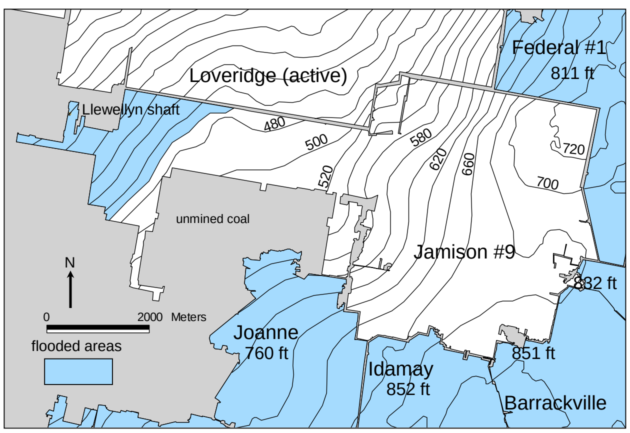

Figure 1. Jamison #9 and adjacent mines with yearly average water levels for the year 2000. Mine floor elevations are shown in feet above mean sea level.

The closed Jamison #9 mine occurs at the western limit of mining on the east side of the coal basin (Fig. 1). It lies in the vicinity of McClellan, WV, at depths from 120 meters (updip along valleys) to 300 meters (downdip beneath uplands), and shares its northern barrier with the active (dry) Loveridge mine. To keep water from seeping across this barrier into Loveridge, Jamison is pumped at Llewellyn shaft to maintain the water level below 145 m (470 ft) elevation. Jamison shares upgradient wetted barriers with Federal #1, Barrackville, Idamay, and Joanne mines. Thus four mines are contributing barrier leakage to Jamison, and all this water is pumped out at Llewellyn shaft.

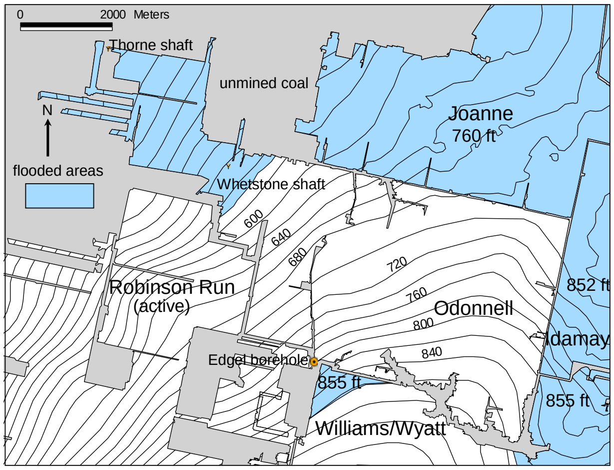

Figure 2. Odonnell and adjacent mines with yearly average water levels for the year 2000. Mine floor elevations are shown in feet above mean sea level.

The closed Odonnell mine is located about 12 km south of Jamison, in an essentially identical hydrogeological setting (Fig. 2). It lies in the vicinity of Wyatt, WV, at depths from 75 meters (updip along valleys) to 240 meters (downdip beneath uplands). It shares a portion of its southern barrier with the active (dry) Robinson Run mine, and is pumped at Thorne and Whetsone shafts to maintain the water level below 180 m (590 ft) elevation. Odonnell shares upgradient wetted barriers with Joanne, Idamay, and portions of the Williams mine, which all contribute to inflowing barrier leakage.

If the assumption can be justifiably made that the only significant inflows are from barrier leakage (i.e., vertical recharge is negligible), then the only discharge is to pumping at rate Q_{pump}, and a mass balance quantifying barrier leakage with Darcy's Law can be invoked:

$$Q_{pump} = \sum_{i=1}^{n} K_h b L_i \frac{\Delta h_i}{w_i} \qquad \textbf{(1)}$$

where

Q_{pump}	= pumping discharge [L^3/T]
b	= coal thickness [L]
L_i	= barrier segment length [L]
Δh_i	= head difference between water level in "wet" mine and average mine floor elevation in "dry" mine [L]
w_i	= barrier thickness [L]

Zero vertical infiltration (roof leakage) is assumed in applying equation (1), under the assumption that, at the depths of cover for these two mines, this recharge from infiltration is negligible. This assumption relies on settlement of overlying strata and reduction of vertical permeability after mining (Hill and Price, 1983; Stoner, 1983). However, it fails to account for the hydraulic impact of areas where vertical connections are naturally high (underlying stream valleys). Therefore, the K_h values derived from this analysis must be considered maximum values.

Application of equation (1) involved discretizing wetted barriers into segments that are uniform in thickness and calculating the above parameters for each segment. Under assumption of spatial homogeneity in coal properties, K_h may be varied until calculated barrier leakage equals known pumping discharge. Only surrounding upgradient barriers contribute leakage to the pumped mines. The water level in the pumped (downgradient) mines is not material in calculating the hydraulic gradient because the leaking barrier is dry on the pumped mine side. For purposes of numeric modeling, dry pit floor conditions were maintained by heads estimated as 1) the average elevation of the pit floor across the length of a given barrier segment in places of near uniform slope or 2) the elevation of the pit floor at the midpoint of the barrier segment in the case of non-uniform slope.

This procedure involves two key assumptions. First, it is assumed that coal barrier properties are spatially homogeneous. Second, it is also assumed that K_h is independent of barrier thickness and represents a property of the coal at given depths. The effects of barrier thickness are accounted for by the gradient.

Results

Jamison was divided into 23 wetted barrier segments ranging from 5 m to 120 m in thickness and up to 59 m in hydraulic head difference. Odonnell was divided into 14 segments ranging from 15 m to 180 m in thickness with head differences up to 40 m. Water budgets for both mines were computed for each calendar year from 1992 to 2000, years for which sufficient water level and pumping data were available. Some water levels were interpolated values.

Modeling of K_h using an isotropic model

Values of spatially uniform K_h were calculated directly from equation 1 (isotropic model) for each of the 9 years of record for each mine (Table 1). K_h in the Jamison models ranged from 0.05 m/day to 0.13 m/day with median 0.089 m/day. K_h in the Odonnell models ranged from 0.03 m/day to 0.15 m/day with median 0.082 m/day. The average of the 18 values is 0.091 m/day.

Modeling of K_h using an anisotropic model

For the Jamison and Odonnell results, an anisotropic model was applied to see if these results deviate significantly from those obtained using the isotropic model. The value of the angle between face cleat and barrier orientation was estimated for each of the barrier segments for both mines. The regional value reported by Stoner (1983) of N 70° W was used as an estimate of face cleat direction. The angle of the butt cleat to the face cleat was estimated at 90°.

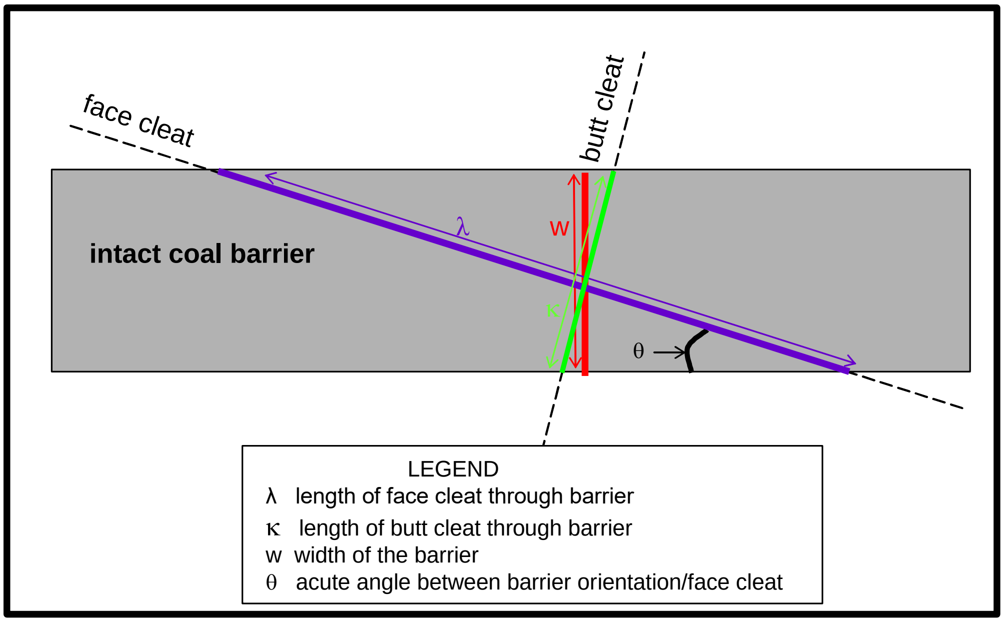

Figure 3. Schematic diagram showing intersection between coal face/butt cleats and a mine barrier. Measurements are indicated by arrows.

Using these angles, a conceptual model of cleat intersection with the barrier was developed to estimate the length of fluid flow through fractures within each barrier. For Fig. 3 showing barrier segment I, the following lengths were calculated:

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

$$\kappa_i = \frac{w_i}{\cos\theta_i}$$

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

These distances were used to calculate conductance for each barrier, in compliance with Q_{pump} similar to equation (1). Butt cleat lengths across barriers are generally shorter given dominant barrier orientations. Values of face cleat K were adjusted iteratively using a value of anisotropy (K_f/K_b) of 1.8, the result obtained by Stone and Snoeberger (1977) in the Powder River Basin, Wyoming. For anisotropic media, equation (1) becomes for n barrier segments in a single mine:

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

By varying K_f for Jamison and Odonnell under the assumed anisotropy, values of K_f and K_b were estimated for the two mines from 1992 through 2000, as shown in Table 1. Average values for the Jamison model were 0.09 m/day (K_f) and 0.05 m/day (K_b), and in the Odonnell model were 0.16 m/day (K_f) and 0.09 m/day (K_b).

Table 1.Calculated barrier K_h, K_f, and K_b

mine	**calendar year**	**K_h (m/day)**	**K_f (m/day)**	**K_b (m/day)**
Jamison	2000	0.102	0.112	0.062
Jamison	1999	0.089	0.098	0.054
Jamison	1998	0.057	0.063	0.035
Jamison	1997	0.063	0.070	0.039
Jamison	1996	0.085	0.095	0.053
Jamison	1995	0.134	0.152	0.084
Jamison	1994	0.106	0.120	0.067
Jamison	1993	0.049	0.056	0.031
Jamison	1992	0.095	0.110	0.061
Odonnell	2000	0.034	0.055	0.030
Odonnell	1999	0.080	0.135	0.067
Odonnell	1998	0.081	0.132	0.073
Odonnell	1997	0.062	0.104	0.054
Odonnell	1996	0.082	0.138	0.076
Odonnell	1995	0.098	0.167	0.093
Odonnell	1994	0.121	0.209	0.116
Odonnell	1993	0.153	0.270	0.150
Odonnell	1992	0.152	0.271	0.150
	mean	**0.091**	**0.131**	**0.072**
	median	**0.087**	**0.116**	**0.650**

Conclusions

In two locations where field data was available, hydraulic conductivity for abandoned deep mines has been calculated using a Darcian approach. The model assumed spatially homogenous coal, negligible vertical recharge at depth, and barrier thickness to be represented by gradients. Hydraulic conductivity estimates for long sections of leaky barriers in the Pittsburgh coal range from 0.03 m/d to 0.15 m/d using an isotropic model for two deep mines in northern West Virginia. Results reflect maximum values as all pumping outflow is attributed to inflow across barriers from adjacent flooded mines. Thus calculated values are slightly higher than most previously reported. Using an anisotropic face/butt cleat model based on Stone and Snoeberger's (1977) ratio of 1.8, values of from 0.05 to 0.27 (face cleat K_f) and from 0.03 to 0.15 m/d (butt cleat K_b) were obtained.

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