ground water

Ground Water Flow Parameterization of an Appalachian Coal Mine Complex

by William R. Winters[1] and Rosemary C. Capo[2]

Abstract

We examined a large (240 km^2) northern Appalachian bituminous coal basin (Irwin Syncline, Westmoreland County, Pennsylvania) comprising 27 mine complexes with nine major (> 2.5×10^3 L/min) discharges. The synclinal basin was divided into seven subbasins based on equilibrium hydraulic relationships established during the past 25 years. Recharge rates, mine pool velocity, and residence times respond to hydraulic changes in the overburden induced by mine subsidence. The estimated maximum depth for subsidence fractures is 60 m (30 times mined thickness) with recharge rates decreasing significantly in subbasins with thicker overburden (> 75 m). Calculated subbasin recharge rates range from 2 to 6×10^{-4} L/min/m^2 and are significantly lower than the previously used rate for the basin. Residence time of ground water in the Irwin subbasins calculated using average linear velocity ranged from one to five years and were more consistent with field observations than estimates obtained using discharge and basin volume area. A positive correlation ($r^2 = 0.80$) exists between net alkalinity of the mine water-impacted discharges and residence time in the mine pools. Our results for the Irwin coal basin suggest that use of a subbasin approach incorporating overburden depth, mining methodology, and the extent of postmining inundation will lead to improved determination of ground water flow parameters in mined watersheds in northern Appalachia and elsewhere.

Introduction

Flooded underground mine complexes are common throughout the coal fields of the world, producing acid and metal contaminated discharges that impact regional ground water flow systems as well as the water quality of their receiving streams. Effects of coal mining on aquifer systems range from minimal to severe depending on topography, geologic structure, nature of the overlying strata, mine depth, and mining method employed (Dixon and Rauch 1988; Donohue and Parizek 1994; Elsworth and Liu 1995). Thus, underground mine complexes present numerous problems for the quantification of basin hydraulic parameters such as recharge rate, ground water velocity, and residence time. Regional ground water flow models must quantify these parameters and their subsequent impacts on residence time and discharge geochemistry.

Mining in most Appalachian coal basins began in the late 1800s when mine designs involved simple gravity drainage to the portal. Mine barriers in many older mines were created to allow separate ventilation systems in neighboring mines. These barriers tended to be very thin and, upon closure, provide little resistance to water flow, eventually allowing mine water to migrate into and flood adjacent mines. A common mine pool can form, creating a very large underground drain for overlying aquifers.

Most older mines (pre–1980) were developed up the structural dip (updip) to facilitate gravity drainage of water to the mine opening (portal). With the passage of the Surface Mining Control and Reclamation Act in 1977, gravity drainage to the portal was outlawed and downdip mining techniques were mandated. With the switch to downdip techniques and the increased ability to pump large volumes of water, mine development shifted to deeper coal reserves in basin interiors. Deeper mines result in greater overburden thickness (rock overlying the coal seam) and confined aquifer conditions for water at depth. New mines opening adjacent to older flooded mines required substantial barriers to prevent mine water from migrating into active works.

[1]Corresponding author: Department of Geology and Planetary Science, 200 SRCC, University of Pittsburgh, Pittsburgh, PA 15260; and Department of the Interior, Office of Surface Mining, Pittsburgh, PA 15220; (412) 937–2105; fax (412) 412-937-3012; bwinters@osmre.gov

[2]Department of Geology and Planetary Science, 200 SRCC, University of Pittsburgh, Pittsburgh, PA 15260; (412) 624–8873; rcapo@pitt.edu

These larger barriers allowed large differences in hydraulic head to develop between active and abandoned mines. As mining progressed longitudinally, large basins separated into smaller, hydraulically related mine pools. Separate and distinct pressure relief points developed in stream valleys over, or adjacent to, the flooded mines, allowing mine-contaminated ground water to exit to the surface.

Postmining discharges have been traditionally treated as discrete entities. Thus, the relationship between individual mine discharges, associated underground network of interconnected mines, basinwide precipitation events, and regional variations in overburden thickness remains unresolved. Improved definition of the hydraulic attributes of large mined basins and better understanding of the physical and chemical processes at work in coal mine-impacted basins will lead to better modeling efforts, more efficient remediation methods, and prevention of costly and environmentally devastating postmining discharge scenarios. For example, the cost of coal mine discharge remediation in the United States has been estimated to be $1 million per day (Kleinmann 2000), while Canada spends in excess of $3 billion a year (Walter et al. 1994).

Numerous studies of individual mine pools have determined the effects from mining on storativity, hydraulic conductivity, and ground water flow patterns, but have not established the overall hydraulic relationships that develop in large mined basins. Discharge estimates generated from single mines governed by mine pool pumping or by free flowing discharges have shown considerable variation (Stoner 1983; Williams et al. 1993). To better quantify the physical and geochemical impacts of underground mining on regional ground water flow, models must be extended from individual mine pools to include the larger basin hydrogeologic system. Unfortunately, field data for large coal basins are often lacking while current methods for estimating hydraulic parameters may not lead to accurate physical depiction of the hydrologic system (Brusseau 1998).

We determined the hydraulic relationships between the underground mines and the overlying aquifer system in a typical large (240 km^2) northern Appalachian bituminous coal basin (Irwin Syncline, Westmoreland County, Pennsylvania). Subbasins were delineated, recharge rates calculated, and residence time estimated for each subbasin within the larger mined synclinal basin. Comparison of our results with field data and ground water models developed in similar basins suggest an improved methodology for determining hydraulic parameters associated with ground water flow in underground mine aquifers.

Geologic and Hydrogeologic Setting

The Appalachian coal basin extends from northern Pennsylvania to Alabama in a narrow band > 1300 km long, but < 200 km wide. Appalachian basin stratigraphy is characterized by cyclic sedimentary sequences with 15 to 30 m separations between coal beds (Brady et al. 1998). Coal basin depositional environments produce an interfingering of coarse- and fine-grained sediments. This stratigraphic setting produces very heterogeneous ground water flow systems with large contrasts between horizontal and vertical hydraulic conductivity. Structural deformation and stress relief fracturing create secondary porosity that dominates the aquifer matrix in much of the region (Schubert 1980).

In the northern Appalachian area (Figure 1), the intensity of orogenic folding and faulting decreases to the west with small, parallel folds striking northeast-southwest (Johnson 1925). Appalachian basin coal butt and face cleat fractures tend to be parallel and perpendicular, respectively, to the regional fold axis (McCulloch et al. 1976). Recharge to the stress-relief fracture system occurs mainly along the ridge top and valley side walls. Bedding plane partings and stress-relief fractures parallel to valley walls and perpendicular to valley bottoms serve as the primary conduits for ground water flow (Wyrick and Borchers 1981; Hobba 1991). Average hydraulic conductivity and storativity decrease with depth (Stoner 1983).

The Irwin Syncline (Figure 2) is typical of the numerous coal-bearing structural basins formed along the Allegheny orogenic front, characterized by narrow, moderately incised valleys with ridge tops ~400 m above mean sea level. It strikes northeast-southwest and plunges 0.7° to the southwest (Johnson 1925). The western flank maintains a fairly constant dip (1°) throughout the study area, but the northeastern limb is steeper (~2°) and gradually flattens to the south.

The Pennsylvanian age (~290 Ma) Pittsburgh Coal is the major coal seam mined in the Monongahela Group that spans the northern Appalachian area (Figure 3). Overburden rocks of the Pittsburgh Formation, ~70 to 85 m thick in the area (Williams et al. 1993), progress through cyclic limestone, shale, and sandstone sequences. The Benwood Limestone, a fresh water limestone above the Pittsburgh Coal, contributes significant alkalinity to Irwin Basin waters; extensive sequences of shale and calcareous shale below the coal provide an impermeable base for the hydrogeologic system (Brady et al. 1996).

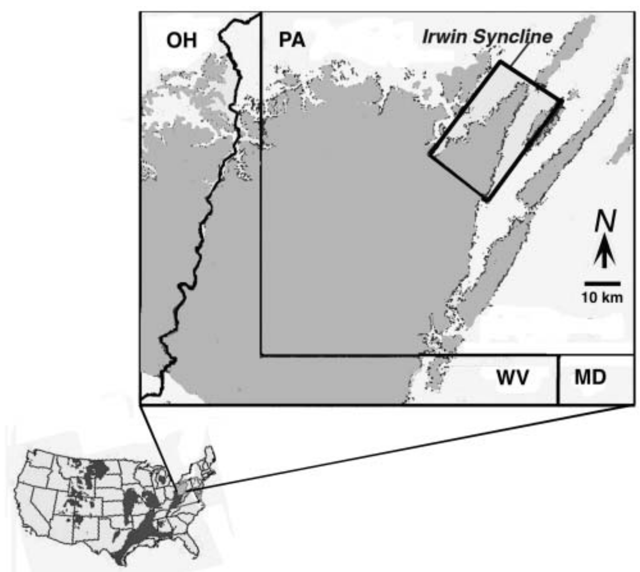

Figure 1. The Irwin coal basin is located along the northeastern end of the Appalachian bituminous coal fields of the United States, shown in the shaded regions (modified from U.S. Geological Survey Open File Reports 96–280 and 96–279).

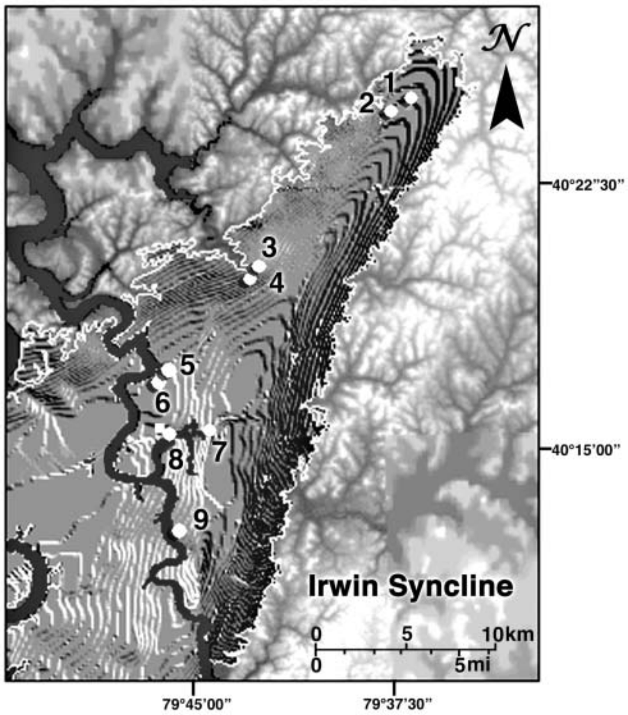

Figure 2. Topography, depth to coal, and mine water discharge locations in the Irwin Syncline (modified from Winters et al. [1999]). GIS coverage from digitized U.S. Geological Survey digital elevation model 7.5 minute quadrangle maps. Contour lines represent overburden thickness above the Pittsburgh Coal Seam; contour interval is 20 feet (Winters et al. 1999). Major discharge locations determined with a global positioning system are 1—Delmont, 2—Export, 3—Coal Run, 4—Irwin. 5—Upper Guffey, 6—Lower Guffey, 7—Lowber, 8—Hutchinson, and 9—Euclid.

Mining of the Pittsburgh Coal Seam in the Irwin Basin began in the late 1800s and ended in 1984. Given the watershed size (4566 km^2) and regional nature of the river (85 m^3/sec), the premining ground water flow system in the Irwin Syncline most likely discharged to the Youghiogheny River (Figure 2) (Herb et al. 1981). Currently, ground water flow in the basin is controlled by 27 interconnected subsurface mine complexes. In the northern portion of the basin, precipitation presumably infiltrates along the flanks of the syncline and moves along the mine floor toward the basin axis, driven by gravity gradients perpendicular to structural strike. This recharge mechanism is a consequence of very thin overburden and abundance of unflooded works in this part of the basin. In deeper portions of the basin, recharge is received from overlying aquifers and along the outcrop areas on the basin periphery. Once in the mine void, ground water flows down the axial plunge and exits in the middle and lower basin reaches at nine major discharge points (Figure 2).

Mining Methodology and Effects

Room and pillar mining removes coal via a series of long, parallel tunnels (entries) driven down the structural dip from the portal. A series of shorter tunnels are cut perpendicular to the entries, forming an underground maze with a checkerboard pattern. The series of squares formed by the entries and crosscuts are called pillars and are left to support the immediate roof. Upon initial mine development, ~50 % of the coal is removed in the entries, leaving 50% in the pillars to support the roof. Upon full mine development, many mining companies cut slices or slabs from these pillars on retreat from the mine in a practice called retreat or secondary mining. In most instances, the weight of the overburden, now residing on a smaller bearing surface (pillar), causes the pillar to collapse. The roof, now unsupported, falls into the mine void resulting in a progressively upward collapse of the overburden. The resulting subsidence profile is similar for all high-extraction mining methods, but differs in magnitude, depending on geologic and mining variables (Figure 4).

At significant depth (> 30 times mined thickness, t [Singh and Kendorski 1981]), the subsidence profile is divided into four distinct zones. The cave or gob zone (zone 1 in Figure 4) is the immediate overburden that falls into the mine void. It is characterized by angular- to slab-shaped material from 0.15 to 1.0 m in diameter or length, extending upward 2 to 10 times the mined thickness. The vertical development of the cave zone is mitigated in overlying layers by bulking of the material falling into the mine void. This phenomenon results from an increase in volume of the collapsed material relative to its in-place volume. Bulking of the material provides support for overlying strata, resulting in less vertical displacement in overlying strata.

A fractured zone (zone 2 in Figure 4) overlies the cave zone and is characterized by strata deformation producing fractures, bedding plane separations, and dilation of existing fractures. This zone extends upwards 10 to 24 times the mined thickness with fracture extent dependent on the geotechnical properties of the strata. Soft strata (e.g., shale,

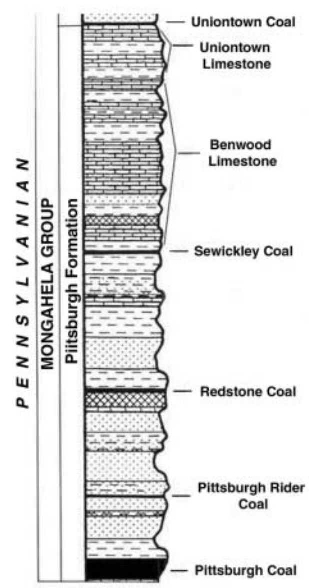

Figure 3. Generalized stratigraphic column for Pennsylvanian age rocks in southwestern Pennsylvania. The ~290 Ma Pittsburgh Coal Seam is the basal unit of the Monongahela Group (~115 m thick in the area), which progresses through cyclic limestone, shale, and sandstone sequences. In the Irwin Syncline region, the thickness of the Benwood Limestone ranges from 3 to 20 m and the Pittsburgh Coal averages 2 m thick (Johnson 1925).

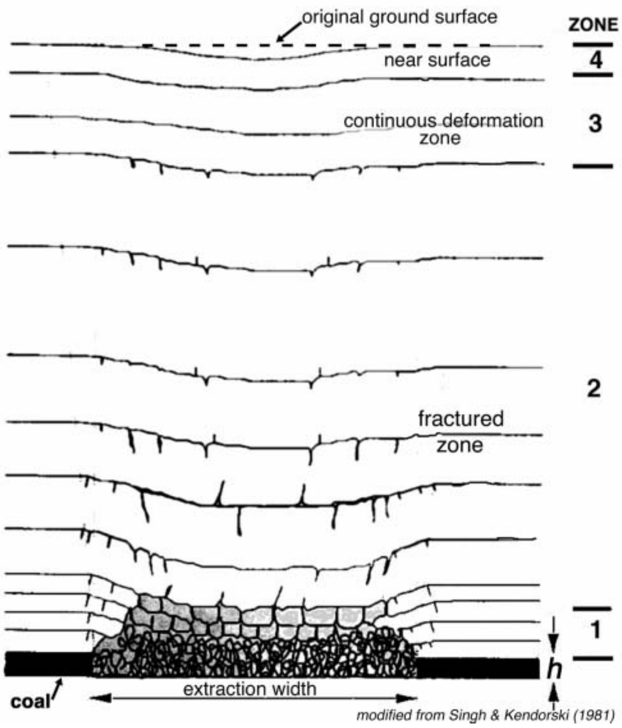

Figure 4. Typical subsidence profile incorporating hydrogeologic impacts of mining subsidence. In zone 1, the caved zone thickness equals 2 to 10 times the thickness of the mined out coal. In zone 2, the fractured zone thickness is 10 to 24 times the thickness of the mined out coal. In zone 3, the continuous deformation zone is 24 to 64 times the thickness of the mined out coal. In zone 4, surface zone extends down to 15 m. Modified from Singh and Kendorski (1981).

claystone) deform easily, leading to reduced fracturing. Conversely, hard strata (e.g., sandstone, limestone) are prone to brittle deformation, therefore increasing fracturing.

The aquiclude, or continuous deformation, zone (zone 3 in Figure 4) overlies the fractured zone and extends upward 24 to 64 times the mined thickness. It is also characterized by less deformation and fracturing than the underlying fractured zone. In the aquiclude zone, vertical displacement has been lessened by dilation of existing fracture planes and material bulking in the cave zone.

The surface zone (zone 4 in Figure 4) comprising the upper 15 m of strata overlies the aquiclude zone. Fractures may appear on the land surface, but are dependent on surface strata composition.

The amount and degree of subsidence-induced fracturing is a function of many variables that fall into two categories—(1) geology related (overburden composition, in situ fracture zones, etc.); or (2) mining related (mining depth, method, degree of extraction). Geologic variables relate directly to the strength of geologic material and the ratio of hard to soft rocks (Whittaker and Reddish 1989). Mining-related variables seek to correlate maximum subsidence potential with overburden thickness (more overburden equals trough subsidence), mined thickness (higher mined height equals more subsidence), and panel or mined width (greater width equals more subsidence). In Appalachia, average maximum surface subsidence is 50% to 60% of mined seam thickness (Karmis and Agioutantis 1992).

Mining alters the natural ground water flow system by the introduction of vertical fractures, bedding plane separations, and mine voids that lead to development of a high conductivity layer at depth (Booth 1986; Borchers et al. 1991; Booth et al. 1997). Underground mining results in heterogeneous flowpaths that affects ground water flow mechanisms on different scales (Aldous and Smart 1988; Wunsch et al. 1996). In deeper mining scenarios, the bridging effects of cave zone development, in combination with the plastic deformation properties of soft rock, do not significantly affect overlying aquifer units (Singh and Kendorski 1981; Booth et al. 1997).

Irwin Basin: Study Methodology

Irwin Basin Subsurface Reconstruction

Winters et al. (1999) constructed structural and ground water flow maps for the Irwin Basin using surface topography obtained from U.S. Geological Survey digital elevation data maps and subsurface features developed from Pennsylvania Department of Environmental Protection (PADEP) mine maps. Mine pool elevations from 31 drill holes throughout the basin were obtained from PADEP Operation Scarlift reports for the area (Pullman Swindell

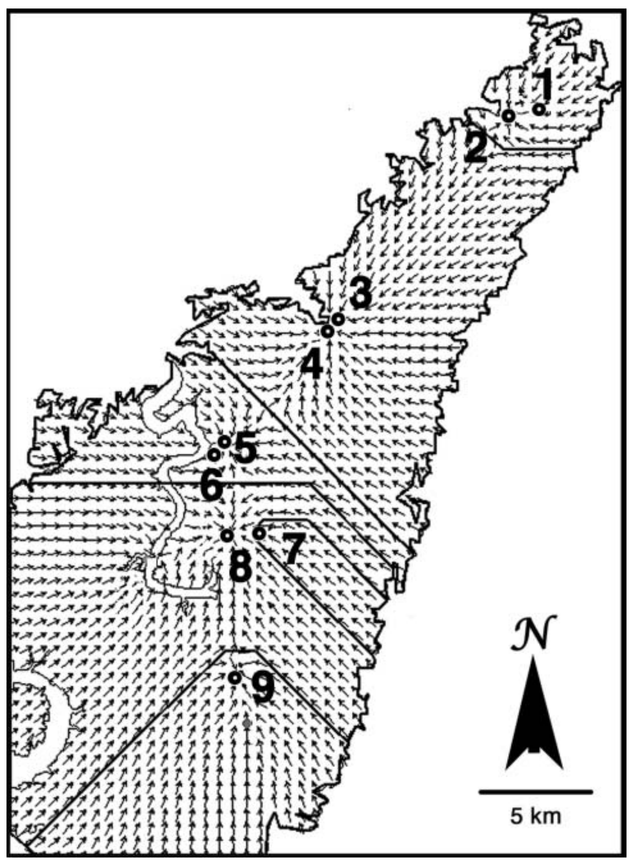

Figure 5. Flowsheds determined from pumping well theory to simulate the combined drawdown effect of the discharges. Ground water flow model developed using the ArcInfo grid. Arrows represent the direction of ground water flow and lines show drainage divides, delineating flowsheds for each subbasin. The discharge points within each subbasin (Figure 2) are roughly analogous to pumping wells (modified from Winters et al. [1999]).

1977). Hydraulic relationships were determined from detailed analysis of known parameters including mining methodology and mine barrier locations. The data were integrated into a geographic information system (GIS). The resulting maps led to division of the Irwin coal basin into hydraulically related subbasins, and development of a ground water flow model (Figure 5). The GIS and resulting flow model were described by Winters et al. (1999).

In this study, we refined the Irwin Subbasin model and quantified mine pool hydrologic parameters to better characterize the regional flow system in the coal basin. Areas for each subbasin within the Irwin Syncline were calculated from digitized mine maps and a GIS of the basin (Winters et al. 1999). Additional field work and mine map investigations led to a better characterization of the Guffey Subbasin and the further division of the Irwin coal basin from five to seven subbasins (Figure 6) from previous work (Winters et al. 1999). Coal Run is now considered separately from the Irwin Subbasin due to the identification of a substantial mine barrier.

Model Assumptions

The Pittsburgh Coal outcrop is used as the hydrogeologic boundary for the regional flow system. For modeling, the average Pittsburgh Coal Seam thickness is 2 m and the postmining coal seam aquifer is assumed to be 14 m thick based on the height (7 t) of the maximum fracture zone in areas of retreat mining for the Pittsburgh Coal Seam in southwestern Pennsylvania (Moebs 1982; Singh 1992). The coal seam is confined in this interval owing to the presence of a nearly impermeable floor and very fine-grained overburden at the maximum expected cave zone height.

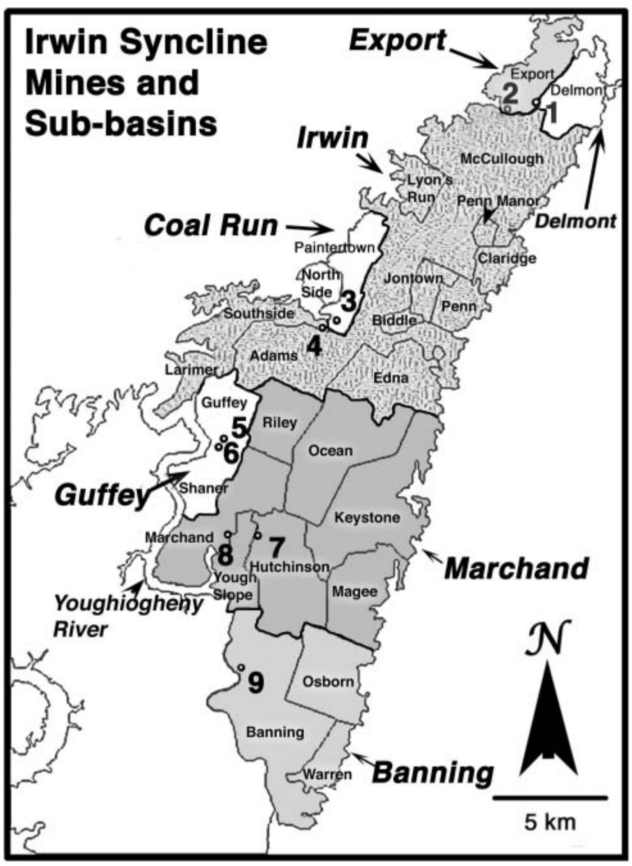

Figure 6. Irwin subbasins delineated by integration of hydraulic head distribution, mine barrier, and discharge location. Mine complexes are labeled. Modified from Capo et al. (2001).

The source term (precipitation) within the basin was modeled assuming constant average precipitation, evenly distributed throughout the basin. In reality, spatial and temporal variations in the source terms can occur, due to variations in weather patterns and other hydrologic factors. However, seasonal variation in static water elevations should not significantly affect the regional flow patterns of ground water basins (Freeze and Witherspoon 1966). Correspondingly, we do not expect the hydraulic relationships between subbasins to change substantially when differing flow rates and/or heads are imposed on the system, as long as the input data are confined to a small time interval (days).

The subsurface conditions in the Irwin Syncline include fractured zones, leaky overlying aquifers, and mine barriers. Consideration of these factors on a regional scale is extremely difficult. To overcome this problem, data were collected over a very small time interval (days) to produce a snapshot in time of equilibrium conditions. The steady-state flow condition assumes that the total ground water source inflow equals total source outflow. This assumption results in a Laplacian constraint on the hydraulic head surface, h, such that the net flux in hydraulic head through time in the x, y, and z directions sums to zero:

$$(\partial^2 h/\partial x^2) + (\partial^2 h/\partial y^2) + (\partial^2 h/\partial z^2) = 0 \qquad (1)$$

Minor transient head conditions are permissible if the increases in net flux in the x direction are compensated by decreases in net flux in the y direction (Freeze and Witherspoon 1966). The gradient induced by the mine void in the vertical direction (z) and the large hydraulic conductivity of the mine void in the horizontal (x) direction result in large hydraulic conductivity contrast between the coal seam aquifer and the over- and underlying strata. As such, ground water flow is predominantly vertical (z) and horizontal (x) along the axial plunge. This contrast between x, y, and z flow directions allows the y component to be eliminated, resulting in a two-dimensional steady-state flow equation:

$$(\partial^2 h/\partial x^2) + (\partial^2 h/\partial z^2) = 0 \qquad (2)$$

The lack of significant hydraulic head changes in the Irwin mine complexes over the last 25 years as shown by Pullman Swindell (1977) and the PADEP mine map repository also justifies the assumption of equilibrium ground water conditions in the Irwin Basin.

Results

Subbasin Recharge Rates

Overburden infiltration is assumed to be the dominant source of recharge to each subbasin. Mining methodology and related hydrogeologic effects significantly alter recharge pathways. High extraction mining causes overburden collapse that enhances recharge due to increases in vertical hydraulic conductivity in overlying aquifers (Hobba 1981; Stoner et al. 1987). Mining-related subsidence also increases overburden permeability and storativity, significantly impacting the hydrogeologic system (Singh and Kendorski 1981; Booth et al. 1997).

In mined basins, recharge rates are often based on site-specific field data extrapolated over large regions. This extrapolation may not yield accurate flux estimation because differences in subsurface geology and mining methodology are not considered. For example, previous workers in the Irwin Basin assumed a basinwide infiltration (recharge) rate of 6×10^{-4} L/min/m^2 based on values from several mines in a similar basin in western Maryland (Pullman Swindell 1977). Given the Irwin Basin area of 2.5×10^8 m^2, the assumed rate (6×10^{-4} L/min/m^2) suggests that 22×10^6 L of water per day should be leaving the Irwin Basin. However, field measurements of discharge volumes (Table 1) indicate that the actual average daily discharge rate in the Irwin Basin is only $\sim 10 \times 10^6$ L/day.

Mine water leaving individual mine pools at discrete locations can be more easily quantified. Assigning individual mine discharge points to hydrologically related units (subbasins) leads to subdivision of the larger basin. An accurate determination of individual subbasin discharge yields a more representative recharge rate for the entire basin. Once the basin is broken into smaller hydrologically related subbasins, differences in recharge can be examined in greater detail. To test this hypothesis and explore the reasons underlying recharge variations, overburden recharge rates were estimated based on the calculated discharge rate from each of the seven Irwin subbasins (Figure 6). The rates were then compared to data acquired during the past 25 years. The recent discharge rates were volumetrically similar to historical flows, allowing changes in flow patterns to be assessed as per Pullman Swindell (1977) and the PADEP mine map repository. Because of the similarity, an average flow was then established from the recent data and used for this study.

Recharge rates (L/min/m^2) were determined by dividing total subbasin discharge rate (L/min), as measured at each respective discharge point, by subbasin area (m^2). The results (Table 2) indicate that recharge rates range from 2.1 to 6.5×10^{-4} L/min/m^2 with lowest rates ($< 3 \times 10^{-4}$ L/min/m^2) in the deeper (> 70 m overburden) subbasins. The field derived subbasin recharge rates for the total Irwin Basin are comparable to results generated from finite difference models of underground Appalachian coal mines. Stoner et al. (1987) reported a range of 3.9 to 2.4×10^{-4} L/min/m^2 while Williams et al. (1993) noted decreasing recharge (infiltration) rates (2.5 to 1.0×10^{-4} L/min/m^2) for mines in Washington County, Pennsylvania.

Williams et al. (1993) also concluded that mining of the Pittsburgh Coal in the area diverted 26.7% of the total precipitation entering the studied watershed. Assuming 91 cm of precipitation falling in the Irwin Basin, the subbasin data suggest recharge to be 26% of total precipitation for shallow mines and 12% for deeper mines (> 70 m overburden) within the overall basin.

Mine water migration across barriers from adjacent mine pools is generally assumed to be a minor contribution to each subbasin's hydrologic budget. However, the high recharge rate (6.5×10^{-4} L/min/m^2) determined for the Guffey Subbasin suggests that either (1) the subbasin intercepts a substantially greater portion of overlying ground water, or (2) the subbasin is receiving recharge from adjacent basins via leakage from peripheral barriers. Extensive retreat mining (e.g., pillar removal) in the area favors the latter explanation. Field observations and subsurface structure suggest that a significant amount of flow is migrating to the Guffey mine pool through mine barriers along the southwest corner of the Irwin Subbasin that abuts the northern edge of the Guffey Subbasin (Figure 6). To better approximate actual mine pool conditions, recharge rates were also calculated for a modified Guffey Subbasin that includes the area and ground water contribution from the southwest corner of the Irwin Subbasin (Table 2).

All subbasins (using the modified Guffey Subbasin definition) yield recharge rates significantly lower than the previously assumed overall Irwin Basin recharge rate (6×10^{-4} L/min/m^2) (Pullman Swindell 1977). The discrepancy can be linked to the amount of cover overlying the basin interior. Overburden thickness is greatest in the interior of the Irwin Syncline (approaching 200 m), thus hindering recharge from reaching the mine void. A negative correlation exists

Table 1
Characteristics of Major Acid and Metal Contaminated Discharges in the Irwin Coal Basin

Subbasin	Map No.	Major Discharges	Q (m^3/sec)	pH	Alkalinity (mg/L)	TDS (ppm)
Delmont	1	Delmont	0.049	4.5	12	685
Export	2	Export	0.050	3.0	0	1030
Coal Run	3	Coal Run	0.043	6.1	132	980
Irwin	4	Irwin	0.489	6.3	117	1459
Guffey	5	Upper Guffey	0.091	6.2	287	1310
	6	Lower Guffey	0.068	6.2	202	1149
Marchand	7	Lowber	0.186	6.1	337	2700
	8	Hutchinson	0.177	6.7	230	N/A
Banning	9	Banning	0.163	7.1	511	3900
		Total	1.316			

Alkalinity and pH values from Weaver (1998) and Capo et al. (2001)

Table 2
Subbasin Data, Recharge Rate, and Residence Time Calculations

Subbasin	Surface Area, A ($m^2 \times 10^6$)	Coal Extracted C_x (%)	Flooding F (%)	Avg. Overburden Thickness (m)	Avg. Discharge Q (m^3/sec)	Discharge Q_L ($L/min^1 \times 10^3$)	Recharge Rate, $L/min/m^2 \times 10^{-4}$
1 Delmont	5.90	65	63	30.5	0.049	3.0	5.0
2 Export	7.28	65	22	36.6	0.050	3.0	4.1
3 Coal Run	7.88	70	28	36.6	0.043	2.6	3.2
4 Irwin	98.6	70	61	68.8	0.489	29.3	3.0
5 Guffey	14.7	75	100	85.0	0.159	9.5	6.5
Guffey (mod.)	18.0	75	100	85.0	0.159	9.5	5.3
6 Marchand	77.0	75	82	93.8	0.263	15.8	2.1
7 Banning	38.7	75	80	95.6	0.142	8.5	2.2

Subbasin	Effective Mine Volume V_e ($m^3 \times 10^6$)	Cross-Sectional Width W (m)	Adjusted Cross-Sectional Area A_x (m^2)	Avg. Linear Velocity v_L ($m^3/sec \times 10^{-5}$)	Avg. Path Length L_f (m)	Residence Time V_e/Q (yr)	Residence Time L_f/v_L (yr)
1 Delmont	4.86	1250	1625	3.02	1357	3.1	1.4
2 Export	2.04	762	991	5.05	1082	1.3	0.7
3 Coal Run	3.04	730	1022	4.21	2134	2.2	1.6
4 Irwin	84.5	3690	5166	9.47	5593	5.5	1.9
5 Guffey	22.1	2425	3638	4.37	1509	4.4	1.1
Guffey (mod.)	26.9	2743	4076	3.89	1981	5.4	1.6
6 Marchand	94.8	6450	9675	2.72	3780	11.4	4.4
7 Banning	46.6	6300	9450	1.50	2164	10.4	4.6

Coal seam thickness assumed to be 2 m.
See text for source and derivation of parameters used.

between subbasin recharge rate and overburden thickness (Figure 7).

Recent subsidence profile research indicates that vertical fractures extend to a maximum of 30 times the mined thickness (30 t) in high extraction areas (Kendorski 1993). In the Irwin Syncline, the average mining height was 2.0 m, corresponding to 60 m for the maximum development of mining-induced vertical fractures. The average overburden thickness in the Irwin Basin interior subbasins (Table 2) is ~90 m with maximum depths approaching 200 m.

In the northern Export and Delmont subbasins, overburden is thin (30 to 35 m thick) with coal outcrops along a majority of each subbasin perimeter; neither subbasin was extensively retreat mined. Drill logs of each subbasin indicate a weathering profile reaching a depth of 15 to 25 m.

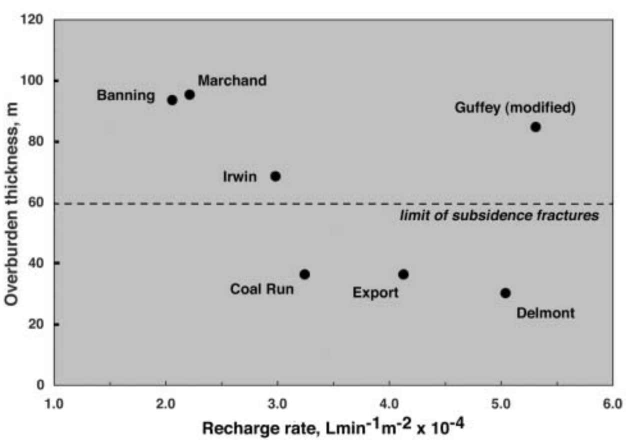

Figure 7. Relationship between recharge rate and overburden thickness. The critical depth for subsidence fracture is 60 m in the Irwin Basin. The deepest subbasins have the lowest recharge rates; an exception is the Guffey Subbasin.

The weathering zone intercepts a large majority of each subbasin leading to direct hydraulic connection between overlying aquifers and the mine, resulting in high recharge rates (4 to 5 × 10^{-4} L/min/m^2) relative to the rest of the basin. These high rates are similar to the estimated recharge rate of 4.7 × 10^{-4} L/min/m^2, for several individual mine sites in the region (Williams et al. 1993).

The centrally located Coal Run and Irwin subbasins have intermediate recharge rates (~3 × 10^{-4} L/min/m^2) which contrast with the deeper (average overburden thickness of > 70 m) Banning and Marchand subbasins (recharge rates of ~2.0 × 10^{-4} L/min/m^2). These deeper subbasins have large areas that were retreat mined, but the bridging effect of overburden collapse likely maintains the integrity of shallow overlying aquitards and limits fracture interception of shallow, overlying aquifers.

Recharge from overlying strata is the major source of subbasin recharge, but in deeper mine complexes a significant portion of the recharge emanates from shallow overburden along the basin perimeter. This water migrates across the mine floor in unflooded sections of the mine, entering the mine pool directly or through barrier compromises in updip portions of the subbasin. These updip, thin overburden areas are also the locations of higher hydraulic conductivity due to natural weathering processes and interfingering of natural and mining-induced subsidence fractures. In the deep subbasins (e.g., Irwin, Banning, Marchand), it is expected that updip recharge zones contribute the majority of recharge to the downdip mine complexes and corresponding discharges.

The range of subbasin recharge rates determined for the larger Irwin Basin demonstrate the error that can occur by using a whole basin or regional approach to hydrologic parameter development. Use of the previously assumed basinwide recharge rate (6×10^{-4} L/min/m^2) results in overestimation of total basin discharge by 100%. Our research indicates that overburden thickness greater than the maximum height of fracture development (60 m) plus the surface zone (15 m) results in lower recharge rates. The degree of retreat mining, updip recharge, overburden lithology, and mine barrier leakage can also lead to significant variations in recharge rate.

Residence Time Determination

The geochemistry of ground water impacted by mine drainage depends on recharge water chemistry, subsurface geology, geochemical reaction kinetics, and reaction time within the mine pool. The residence time of water in a mined basin reflects the length of time subsurface geochemical processes have acted upon it. In the Irwin coal basin, discharges from the downdip southwestern portion of the basin (with a presumably longer residence time) have higher conductivity and increased alkalinity relative to the northern discharges (Weaver et al. 1998).

The residence time of ground water in mine pools has significant geochemical implications, but is rarely determined for large underground mine complexes. Irwin Subbasin residence times were calculated two ways. The most commonly used method is based on the relationship between mine pool area and discharge volume. The second method accounts for flowpath heterogeneity by determining residence time using average linear velocity (v_L) and mine pool path length.

In any ground water flow method using Darcy assumptions, a Reynolds number < 10 is implied. For standard ground water flow, this assumption is valid, but significant deviations from laminar flow are not noted until the Reynolds number exceeds 100 (de Marsily 1986). Assuming fresh water moves through the Irwin Basin with a velocity (v) of 4.2×10^{-5} m/sec (based on field measurements of similar basins [Aljoe and Hawkins 1991]) and a particle size of 1 m (based on the average size of collapsed overburden), the average Reynolds number for the Irwin Basin is ~35, with a range of 15 to 85 for the subbasins. In individual mine voids, turbulent flow conditions can result from high porosity and velocity. When viewed on a regional scale (continuum approach), however, these features make up only a small fraction of the total Irwin Basin. Viewed from a continuum approach, we believe it is within acceptable limits to assume Darcy flow conditions for our residence time calculations.

Discharge Rate Approach

This method assumes that water travels through a mine void at a constant velocity along a flowpath of constant width and length. In underground mine complexes, variations exist in cave zone thickness, percent of coal removed, and mine inundation level. To account for these discrepancies, mine maps from the PADEP mine map repository were used to estimate the percentage of coal removed from each mine within each subbasin. Mine pool elevations were determined from data in Operation Scarlift reports—specifically Scarlift 103–5—and allowed calculation of a beach line in each mine complex. An effective mine volume was calculated by subtracting the percent of coal left in the pillars and incorporating the percent of inundation in each mine. Effective mine volume is the actual void space occupied by water once pillars and inundation levels are accounted for. The resulting effective mine volume (m^3) was then divided by the average discharge rate (m^3/sec) for each subbasin (Table 1) to arrive at volume-discharge residence times that range from 1 to 11 years (Table 2).

A positive correlation exists ($r^2 = 0.71$) between effective mine volume and residence time. The small, shallow, less flooded northern subbasins (i.e., Export, Delmont, and Coal Run) have shorter residence times relative to the deep, > 80% flooded southwestern subbasins (i.e., Marchand and Banning). The northern subbasins have residence times ranging from 1.3 to 3.1 years, while the deeper southern subbasins have residence times approaching 11.5 years. The Banning Subbasin, with the highest residence time, is located in the deepest part of the Irwin Basin and is almost completely flooded. Mine water is removed via a pump located near the Youghiogheny River at the Euclid treatment facility.

Calculated residence times using the discharge-rate approach is a measure of the turnover time of water within the subbasin, allowing for changes in mine volume or discharge rate, but ignoring differences in flowpath lengths and hydraulic characteristics. In typical mine complexes, a significant portion of water flows through collapsed overburden along preferential flowpaths with local variability in hydraulic conductivity resulting in order of magnitude differences in residence times (Aljoe and Hawkins 1991, 1992; Whittaker and Teutsch 1999). This phenomenon is especially prevalent in areas where pillar retreat has not collapsed the overburden (e.g., main entries of room and pillar mines). To account for these shortcomings, residence times for the Irwin subbasins were also determined using an average linear velocity approach.

Average Linear Velocity Approach

Determination of average linear velocity should provide greater accuracy to flow rates in subbasins because it allows flowpath heterogeneity to be implicitly included in the calculation. Mine pool velocity was determined for the Irwin subbasins assuming Darcian flow within the mine void using the following relationship (Fetter 1988):

$$v_L = Q/A_x = -(K/n_e)\ dh/dl \qquad (3)$$

where v_L is the average linear mine water flow velocity.

Subbasin discharge (Q) was determined by summing individual, but hydrologically related, discharges into a total subbasin outflow calculation established from discharge measurements (Table 1). The cross-sectional area term was determined by multiplying the coal seam thickness (2.0 m) by the flowpath width measured perpendicular to flow direction. An effective cross-sectional area (A_x) was approximated by eliminating the mine pillars (as a percentage of in-place coal) from the cross-sectional area term. This cross-sectional flowpath area (A_x) is limited to the area expected to participate in the movement of water within each subbasin; remote areas are not included in the term.

Flow volume (Q) was then divided by the cross sectional area (A_x) to arrive at the average linear velocity of mine water flow (v_L) for each subbasin. Next, average flowpath lengths were established for each subbasin. Most of the subbasins in the Irwin Basin are elliptical, allowing accurate measurements of flowpath lengths and cross-sectional width. The basin shape and corresponding flowpaths for all subbasins (except Banning) were linear, with small components of radial flow at the discharge points. Thus, average flowpath length was determined to be one-half the longest axial length of the flooded portion of each respective subbasin. However, the Banning Subbasin has a significant component of radial flow due to an actively pumping well on its western edge. For this subbasin, cross-sectional width was determined using the radius at the flowpath midpoint with average flowpath length at the midpoint of the longest flowpath. Residence time was calculated by dividing the average flowpath length (L_f) by average linear velocity (v_L). The results are shown in Table 2. Average linear velocities for Irwin Subbasin mine waters range from 1 to 8 m/day; consistent with the range (4 to 20 m/day) estimated by Aljoe and Hawkins (1992) for individual mine sites within the northern Appalachia coal basin.

The Irwin Syncline subbasin residence times determined using the average linear velocity approach are shorter than those determined with the simple discharge/area method (range of 1 to 5 years vs. 1 to 11 years). Using either method, the northernmost basins have the shortest residence times while the southernmost (i.e., Banning and Marchand) the longest. The Export Subbasin has the shortest calculated residence time (~1 year) of the small northern subbasins, although both the Coal Run and Delmont subbasins have similar areas and discharge volumes (0.04 to 0.05 m^3/sec). The difference can be explained by looking at the percentage of each mine flooded and the location of the Export discharge point relative to its structural elevation. The Export Subbasin discharge point is located at the lowest structural elevation within the subbasin, resulting in a shorter flowpath length and much less total flooded mine works (21% inundation vs. 28% to 100% for all other subbasins). Conversely, the Marchand and Banning subbasins have a high percentage of flooded mine works (82% and 80%) and lower discharge volume relative to flooded mine volume, resulting in slower mine pool velocity than northern subbasins (i.e., longer residence times).

Residence Time and Geochemistry

In the Irwin Syncline, the geochemistry of the Export Subbasin indicates that the pool water is acidic (pH = 3) (Table 1). The short residence time for this subbasin (~1 year) suggests that Export mine water does not reside in the mine void long enough to neutralize all acidity through interaction with calcareous overburden rocks. The Banning and Marchand subbasin mine pools, characterized by high conductivity, alkalinity, and sodium, and with circumneutral pH, have the longest residence times. Weaver et al. (1998) postulated cation exchange processes in the Irwin Basin, resulting in increased sodium concentrations in downdip Irwin Basin mine pools as ground waters interact with sodium-bearing clays and shales. Perry (2001) also noted similar phenomena in southwestern Pennsylvania mine pools. Longer residence time leads to higher dissolved chemical loads and equilibration with major overburden mineral species. There is a positive correlation between residence time (calculated by either method) and alkalinity (Figure 8).

Summary and Conclusions

The Irwin coal basin was divided into seven subbasins based on integration of mine barrier location, discharge location, and mine pool elevation data. A ground water flow equation was incorporated into the ArcInfo GIS system (Redlands, California) that allows the model to reflect basinwide changes in precipitation or pumping rates. This work represents the next step in development of a quantitative flow model incorporating basin geometry, overburden thickness, lithology, and geochemistry.

The implications of the hydrogeologic model are as follows.

Recharge rates, mine pool velocity, and residence time generally increase in response to subsidence-induced changes in porosity, storativity, and conductivity. In the Irwin coal basin, recharge rates ranged from 2.1 to 5.3 $\times 10^{-4}$ L/min/m^2 and were dependent on overburden thickness, mining methodology, and overburden fracture characteristics. Average overburden thickness > 70 m resulted in lower recharge rates due to the lack of vertical subsidence fractures extending upward to the level of the stress-relief fractures.

Use of basinwide estimates for recharge rates can lead to large errors in determination of basin discharge. The previously used rate for the Irwin Basin (6.0×10^{-4} L/min/m^2) leads to 100% overestimation of actual basin discharge volumes. However, the commonly applied coal industry rate of 4.7×10^{-4} L/min/m^2 (Parizek 1971) could be a reasonable estimate for relatively shallow (< 60 m) overburden

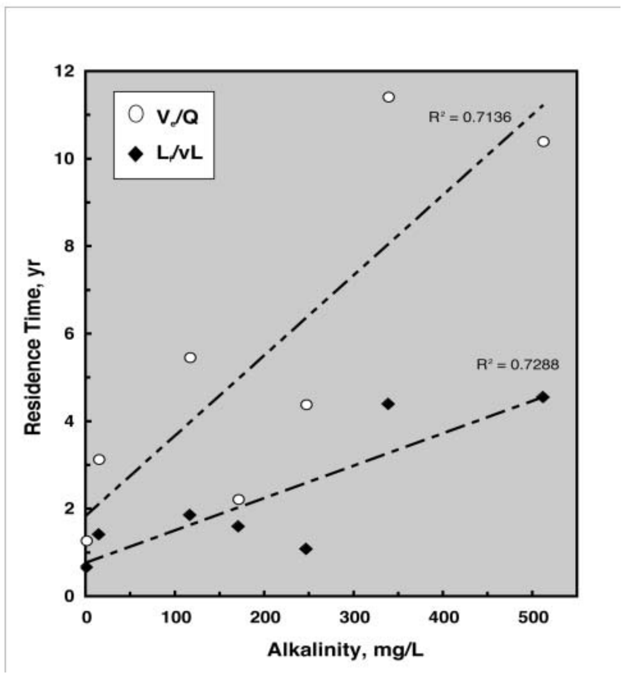

Figure 8. There is a positive correlation between discharge alkalinity and residence time calculated by either the volume-discharge (V_e/Q) or linear velocity (Q/A) methods; however, the one to five year range of the latter best fits available field data for mine pool residence time.

situations that are controlled by recharge from fracture-induced subsidence. Retreat mining, updip recharge, and mine barrier leakage can also lead to significant variations in recharge rate and must be considered in rate determinations.

In contrast to the traditional mine discharge/volume approach, residence times determined by average linear velocity implicitly include flowpath heterogeneity and are more consistent with field determined estimates. Irwin Subbasin residence times ranged from 8 months to 5 years, with longer residence times associated with increased alkalinity in Irwin Basin mine waters. Average mine water velocity determinations for the Irwin subbasins ranged from 1 to 8 m/day.

Many large, flooded bituminous coal basins are found in the coalfields of the world. Most of these basins have been largely ignored due to the complexity of the postmining hydraulic relationships that develop in these regionally extensive basins. Determination of recharge rate and residence time for every mine complex within a large coal basin is not always feasible. However, these results suggest that division of a large mined basin into several hydrogeologically related subunits is achievable and can lead to significantly improved predictions of basin mine water discharge.

The Irwin Basin study establishes the utility of subbasin modeling to better quantify postmining hydraulic parameters such as residence time and recharge rate in a typical flooded bituminous basin. The methods used to calculate the hydraulic parameters are based on basic hydrogeologic concepts and should be applicable to other bituminous basins. The determination of accurate hydrologic parameters is a critical step in developing predictive models of discharge rates and geochemical fluxes to quantify the environmental impact of large, flooded mine complexes.

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