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Mine-Water Flow between Contiguous Flooded Underground Coal Mines with Hydraulically Compromised Barriers

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ABSTRACT

Groundwater flow entering closed contiguous underground coal mines may be strongly influenced by leakage across inter-mine barriers. This study examines a complex of multiple closed and flooded mines that developed into a nearly steady-state groundwater flow system within 10 to 50 years after closure. Field water-level observations, mine geometry, barrier hydraulic conductivity, recharge rates, and late-stage storage gains were parameterized to match known pumping rates and develop a fluid mass balance. Vertical infiltration (recharge and leakage) estimates were developed using a depth-dependent model based on the assumption that most vertical infiltration is focused in areas with <75 m of overburden. A MODFLOW simulation of the nearly steady-state flow conditions was calibrated to hydraulic heads in observation wells and to known pumping rates by varying barrier hydraulic conductivity. The calibrated model suggests significant head-driven leakage between adjacent mines, both horizontally through coal barriers and vertically through inter-burden into a shallower mine in an overlying seam. Calibrated barrier hydraulic conductivities were significantly greater than literature values for other mines at similar depths in the region. This suggests that some barriers may be hydraulically compromised by un-mapped entries, horizontal boreholes, or similar features that act as drains between mines. These model results suggest that post-mining inter-annual equilibrium conditions are amenable to quantitative description using mine maps, sparse observation-well data, accurately estimated pumping rates, and depth-dependent vertical infiltration estimates. Results are applicable to planning for post-flooding water-control schemes, although hydraulic testing may be required to verify model results.

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INTRODUCTION

Underground mines can be classified into two groups: above drainage and below drainage. Above-drainage mines can be further divided according to the direction of mining: up-dip or down-dip. Up-dip mines are "free-draining." Infiltration that reaches these mines flows down-dip along the mine floor and discharges at portals and other connections to the surface, while infiltration that enters down-dip above-drainage mines, and all below-drainage mines, flows to the lowest parts of the mine, resulting in mine flooding. Both groundwater inflow rates and accurate mine maps are essential for predicting the duration of flooding and subsequent mine-water discharge to the surface. Groundwater-inflow estimation for closed underground coal mines constrains recharge to areas of relatively shallow overburden and neglects leakage to deeper mined areas (Winters and Capo, 2004; McDonough et al., 2005; and McCoy et al., 2006).

Published recharge rates applied to mines with relatively small areas of thin overburden cover, therefore, are generally minimum estimates of mine inflows. Mine maps and accurate groundwater-inflow rates (recharge and leakage) are essential to predict the time required for a mine to flood (Younger and Adams, 1999; Whitworth, 2002). Inflow rates and maps alone, however, often yield inaccurate estimates of flooding times for individual mines that are directly adjacent to, and therefore potentially connected to, other mines. In some cases, groundwater-elevation and mine-pool data for multiple mines show highly similar pool behavior between mines, suggesting inter-connection. As a result, an improved understanding of the hydrogeological interactions between adjacent mines that stems from the development of more realistic mine-inflow models and groundwater-flow models depicting conditions in multiple adjacent mines will help clarify and improve predictions of the mine-flooding process. Such information will benefit post-closure operations by allowing more robust sizing, design, and location of mine-water extraction pumps and treatment plants, as well as the development of plans for mine-water control.

Purpose

The purposes of this research are to improve the understanding of post-flooding hydrogeological interactions between contiguous underground coal mines and to present a method for estimating mine inflow that includes vertical infiltration in areas with relatively thick (>100 m) overburden. The improved understanding stems from a steady-state groundwater-flow model that was conceptualized using mined areas, inter-mine barrier thicknesses, and a water budget that is based on known pumping volumes and estimated mine-water inflows. Inter-mine coal-barrier hydraulic conductivities were calibrated using known groundwater elevations and used to calculate horizontal flow between mines. Mine inflows were determined using a depth-dependent vertical infiltration model that is based on published recharge rates and overburden thicknesses. The depth-dependent model offers improved vertical infiltration estimation over earlier methods, especially when the depth of mining becomes relatively deep.

Background

Underground mining creates void space, removes support for overburden, and changes stress fields, frequently resulting in subsidence of overlying strata (Singh and Kendorski, 1981; Booth, 1986). Subsidence features have been categorized into zones that consist primarily of collapsed and rubblized roof rock, vertical fractures, bedding-plane separations, and sagging yet otherwise constrained strata (Singh and Kendorski, 1981; Kendorski, 1993). After mine closure, groundwater extraction ceases, and voids created by mining and subsidence begin to resaturate, resulting in an anthropogenic aquifer (Adams and Younger, 2001). Flooding in these coal-mine aquifers is marked by the initial development of a phreatic surface or "pool" in the deepest portion of the mine (Donovan and Fletcher, 1999), which, with continued flooding, migrates up-dip toward shallower mined areas. Flooding ceases when the pool level reaches the elevation of a "spill point" (Younger and Adams, 1999); alternately, mine inflows may be balanced by loses to barrier leakage or by groundwater-extraction pumping. Flooding progress tends to follow a decaying exponential curve over time, with flooding rates decreasing as the pool level approaches the elevations of either groundwater sources or spill points (Whitworth, 2002). The duration of flooding varies and is controlled by recharge rates as well as the status of adjacent mines. Shallow mines tend to receive more recharge than deeper ones (Winters and Capo, 2004) and therefore tend to flood more rapidly.

Considerable research has been conducted on the hydrogeology of closed underground coal mines, including the chemistry (Banks et al., 1997), volume (Pigati and Lopez, 1999), and seasonality (Pigati and Lopez, 1999; Light, 2001) of mine-water discharges. Others have examined mine aquifer properties such as porosity (Hawkins and Dunn, 2007), specific yield (McCoy, 2002), hydraulic conductivity (Aljoe and Hawkins, 1992), and retention time (Winters and Capo, 2004; Sahu and Lopez, 2009). Flooding histories have been utilized to develop models for prediction of mine flooding (Younger and Adams, 1999; Whitworth, 2002). Recharge-rate estimates for flooding and flooded mines vary from "the miner's-rule-of-thumb" (Stoertz et al., 2001) to calculations that are based on discharge volumes (Winters and Capo, 2004; McDonough et al., 2005), pumping records (Hawkins and Dunn, 2007), and numeric modeling (Stoner et al., 1987; Williams et al., 1993). Recharge is commonly restricted to areas of relatively shallow overburden (<18 m, McDonough et al., 2005; <75 m Winters and Capo, 2004), while leakage is typically not considered a significant source of groundwater for mine aquifers, although it has been shown to occur and even been quantified (McCoy et al., 2006; Leavitt, 1999). Neglecting leakage suggests that deep mines should be "dry" or have limited groundwater inflow, and it results in recharge rates that are significantly greater than published values. This would indicate that leakage should have been included in estimations of inflows to deeper mines. For the purposes of this investigation, recharge and leakage will be un-differentiated and referred to as vertical infiltration.

Unconfined storage in coal mines occurs mainly in the area near the "beach," where the phreatic surface intersects the floor of the mine (Hawkins and Dunn, 2007). Its value has been estimated for different extraction methods based on surface subsidence, coal seam thickness, and the height of roof collapse (McCoy, 2002). It has also been estimated using pumping rates and corresponding changes in hydraulic head (Hawkins and Dunn, 2007). Confined storage, similar to vertical infiltration in relatively deep mined areas, is commonly neglected, although it could represent a significant volume of water in areas of confined groundwater. Inter-mine coal barrier leakage rates have also been estimated (McCoy et al., 2006; Hawkins and Dunn, 2007).

STUDY AREA

The study area for this research includes seven Pittsburgh coal mines located within the Pittsburgh basin, Greene County, PA (Figures 1 and 2). The mines were operated for various periods, but all closed between 1964 and 2004 and as of spring 2013 were in the final stages of flooding, fully flooded, or managed by pumping to control mine-pool levels. Both the fully flooded mines (Crucible and Nemacolin) and the late-stage flooding mines (Pitt Gas and Gateway) contain pools with elevations above the surface of the adjacent Monongahela River (Figures 2 and 3). Mine water is pumped to treatment plants from two locations in the study area (Dilworth and Robena), and also from adjacent mines (Shannopin and Warwick #2), in order to manage pool levels in those mines. The study area is bordered by other Pittsburgh bed mines (Clyde, Humphrey, Shannopin, and Warwick #2) and is partially overlain by a mine in the Sewickley coal bed (Warwick #3) (Figure 2). There are no known surface discharges within the study area, although groundwater began discharging from an adjacent mine (Clyde, Figure 2) during early 2013 after temporary cessation of pumping operations in that mine. The water level in one mine (Mather) is currently unknown, but the mine is believed to be fully flooded with a pool elevation midway between those in adjacent mines (Gateway and Dilworth).

Geologic and Hydrogeologic Setting

The Pittsburgh coal basin, located within the Appalachian Plateau physiographic province (Fenneman, 1938), is bounded by the outcrop of the Pennsylvanian-age Pittsburgh coal bed in parts of southwestern Pennsylvania, southeastern Ohio, and northern West Virginia (Figure 1). The Pittsburgh coal is the basal unit of the Monongahela Group (Figure 4), which also contains the Uniontown Formation. The coal bed varies in thickness but averages 2.0 m, with minor variance in the study area. The Pittsburgh Formation consists of alternating layers of sandstone, limestone, dolomitic limestone, calcareous mudstones, shale, siltstone, and coal (Edmunds et al., 1999). The Sewickley coal, which lies stratigraphically above the Pittsburgh coal by approximately 30 m, is also mined in the basin (Figures 1 and 4), but it is neither as thick nor as extensive as the Pittsburgh coal (Hennen and Reger, 1913). The Dunkard Group overlies the Monongahela Group and varies in thickness up to 365 m (Edmunds et al., 1999). Structural dip of all these strata is typically less than five degrees (Beardsley et al., 1999).

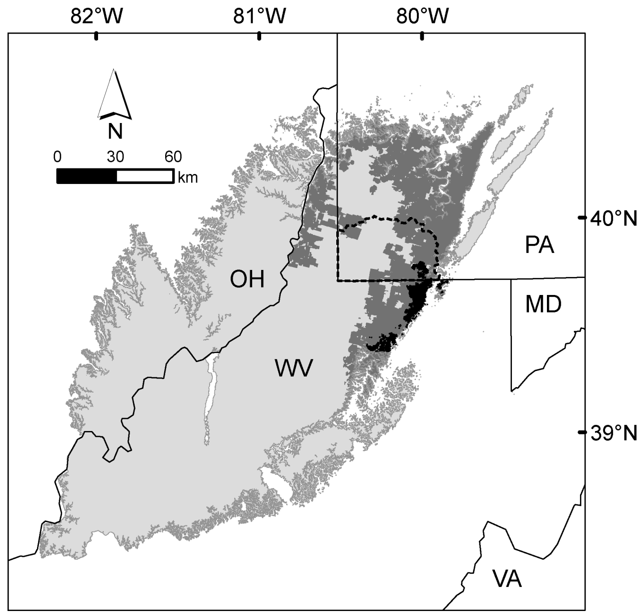

Figure 1. Extent of the Pittsburgh coal seam (light shading) with areas of underground mining in the Pittsburgh (medium shading) and Sewickley (dark shading) seams, in addition to Greene County, PA (dashed line).

Rocks in the Appalachian Plateaus Province tend to have low primary porosity and permeability (Stoner, 1983). Groundwater flow is primarily through networks of stress-relief fractures and bedding-plane separations, which occur along valley walls and parallel to valley bottoms (Wyrick and Borchers, 1981; Kipp and Dinger, 1987). Hydraulic conductivity and storativity tend to decrease with depth (Stoner, 1983), and only a small portion of natural groundwater flow extends to depths greater than 50 m (Stoner et al., 1987). The removal of coal by underground mining and consequent subsidence-induced re-distribution of overburden have considerable impacts on the un-disturbed groundwater flow regime (Stoner, 1983; Booth, 1986). Underground coal mining can also impact surface water by reducing runoff and increasing baseflow (Stoner, 1987). Mining-induced subsidence tends to create large voids and rubble zones with greatly increased hydraulic conductivity (Singh and Kendorski, 1981; Aljoe and Hawkins, 1992; Kendorski, 1993) compared to native coal and overburden (Hobba, 1991). Above rubblized areas, vertical hydraulic conductivity is similarly increased, but this effect decreases with increasing height above the rubble (Palchik, 2003). Post-closure flooding yields coal-mine aquifers (Younger and Adams, 1999), which tend to be locally heterogeneous

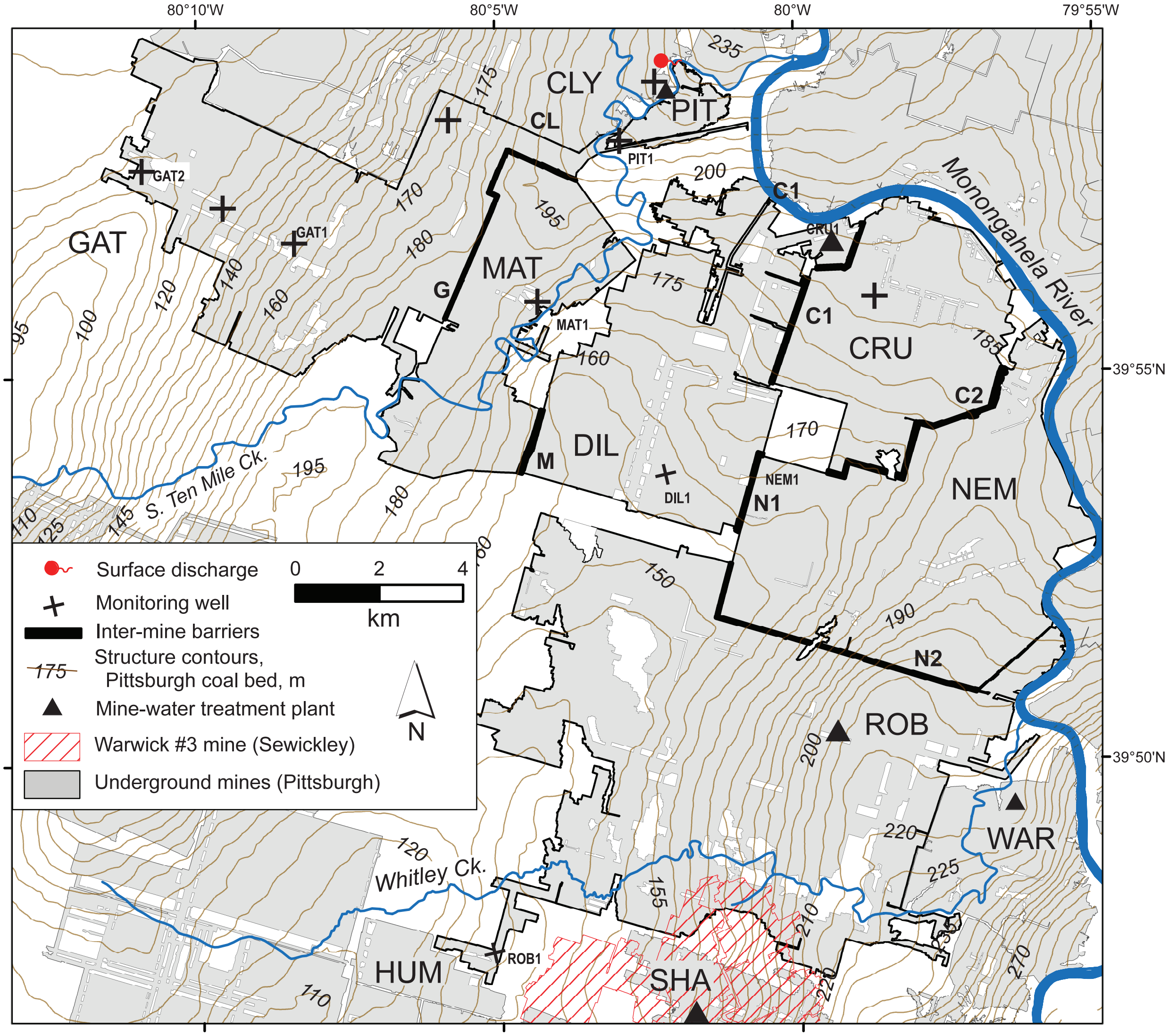

Figure 2. Underground Pittsburgh seam mines in the study area with structure contours of coal bottom (5 m interval), locations of monitoring wells, inter-mine barriers, and mine-water treatment plants (CLY = Clyde; CRU = Crucible; DIL = Dilworth; GAT = Gateway; HUM = Humphrey; MAT = Mather; NEM = Nemacolin; PIT = Pitt Gas; ROB = Robena; SHA = Shannopin; and WAR = Warwick #2).

with preferential flow paths (Aljoe and Hawkins, 1992), due to overburden subsidence, coal pillar geometry, and spatial distribution of highly transmissive main entries (Figure 5). Yet on a mine-wide scale, water levels in different locations within flooded unpumped mines are often fairly uniform (Aljoe and Hawkins, 1992; Figure 3).

Coal-mine aquifers and overlying units can be hydrostratigraphically characterized using overburden subsidence zones (Kendorski, 1993; Figure 4). The *caved zone* contains jumbled overburden collapsed into the mine to heights of 6 to 10t, where t is the thickness of the coal seam, while strata in the overlying *fractured zone* contain vertical fractures and bedding-plane separations extending to heights of 24 to 30t above the mine floor. The *dilated zone* shows bedding-plane separations, increased porosity, and horizontal transmissivity, yet due to the absence of through-going fractures, it acts as the principal aquitard between overlying strata and the fractured and caved zones below. If overburden is sufficiently thick, a *constrained zone* consisting of gently sagging strata may also be present. The *surface fracture zone* contains extended and enlarged pre-existing fractures from the ground surface to 15 m depth. These subsidence zones were developed to describe overburden re-distribution over longwall panels, but similar re-distribution is likely to occur in areas of room-and-pillar mining, especially where pillars are fully extracted (Peng, 1986). The distribution of

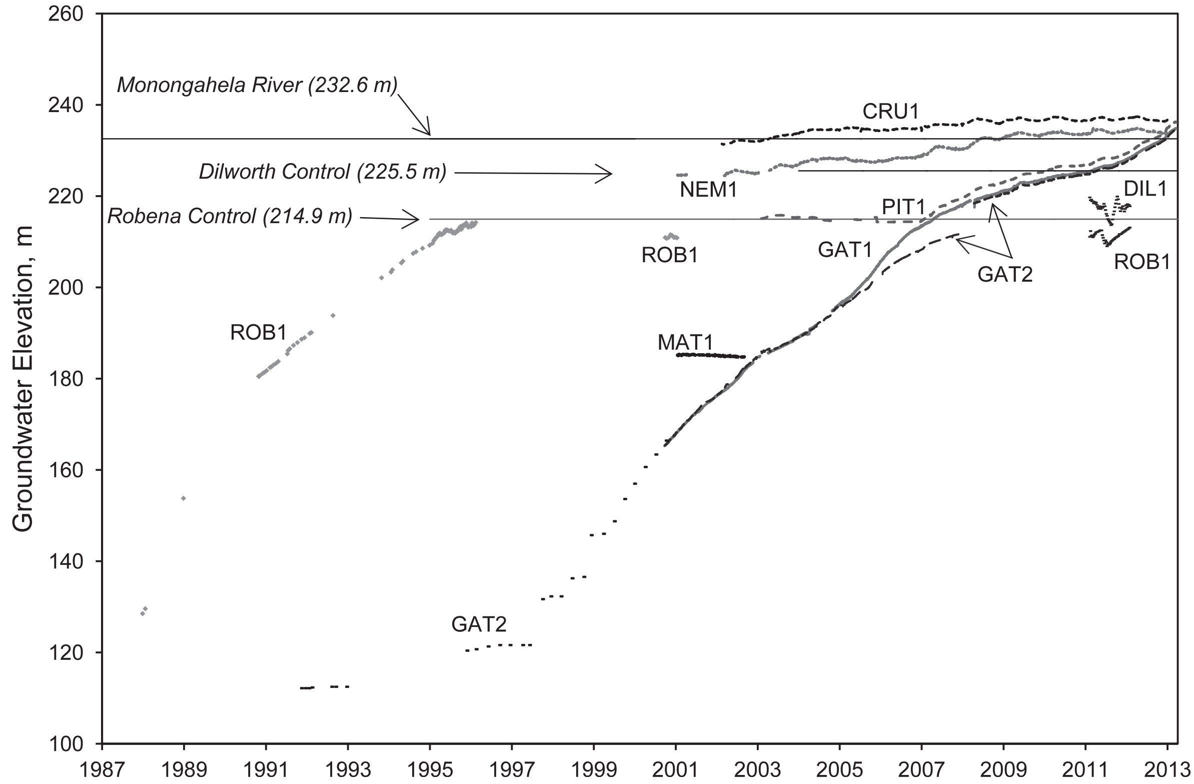

Figure 3. Groundwater elevations indicate fairly uniform pool levels in mines with multiple observation wells (CRU1 = Crucible; DIL1 = Dilworth; GAT1 and GAT2 = Gateway; NEM1 = Nemacolin; PIT1 = Pitt Gas; and ROB1 = Robena). The average surface elevation in the Monongahela River (Maxwell pool) and mine-water treatment plant control levels are indicated by arrows.

subsided materials and overburden thickness has implications for mine-aquifer water budgets including recharge and leakage. In relatively shallow areas (<75 m; e.g., Winters and Capo, 2004) where the surface fracture and fractured zones intersect, recharge rates will be highest , while in areas containing thicker overburden, aquifer inflow will occur as leakage through the dilated zone with relatively low rates. Groundwater movement through overburden is inferred to be predominantly downward into mine voids and collapsed overburden in the caved zone, which are much higher in hydraulic conductivity relative to un-mined coal and rocks. Inter-mine groundwater flow occurs horizontally through coal barriers separating mines (e.g., McCoy et al., 2006; Hawkins and Dunn, 2007), although vertical flow between mines may occur where over- or underlying seams have been mined (Miller, 2000). Flow between mines follows pressure gradients toward discharge locations.

Hydraulic conductivity (K) within coal-mine aquifers is related to the degree of overburden alteration and subsidence and is significantly increased over K within native coal (Harlow and Lecain, 1993). Within the caved zone, K in un-collapsed rooms and mains can be very high, while in "gob" (collapsed) areas, collapsed overburden may reduce K values. Shale and other thinly layered rocks tend to collapse in small pieces, resulting in poorly connected void space, while sandstone and similarly massive rocks tend to collapse in large blocks, leaving significant void space (Palchik, 2002). Strata in the fractured zone will have high vertical hydraulic conductivity (K_V) relative to horizontal hydraulic conductivity (K_H) (Palchik, 2002), yet the number and size of vertical fractures decrease with increasing distance above the mine void, resulting in a similar reduction in K_V (Palchik, 2003).

METHODOLOGY

Groundwater-Head Data

Groundwater elevations were calculated for six monitoring wells (Figure 2) using depth-to-water measurements and pressure transducers. Between September 2000 and November 2005, pressure measurements were made using vented transducers, while after November 2005 measurements were recorded primarily with sealed transducers and corrected using barometric-pressure data collected

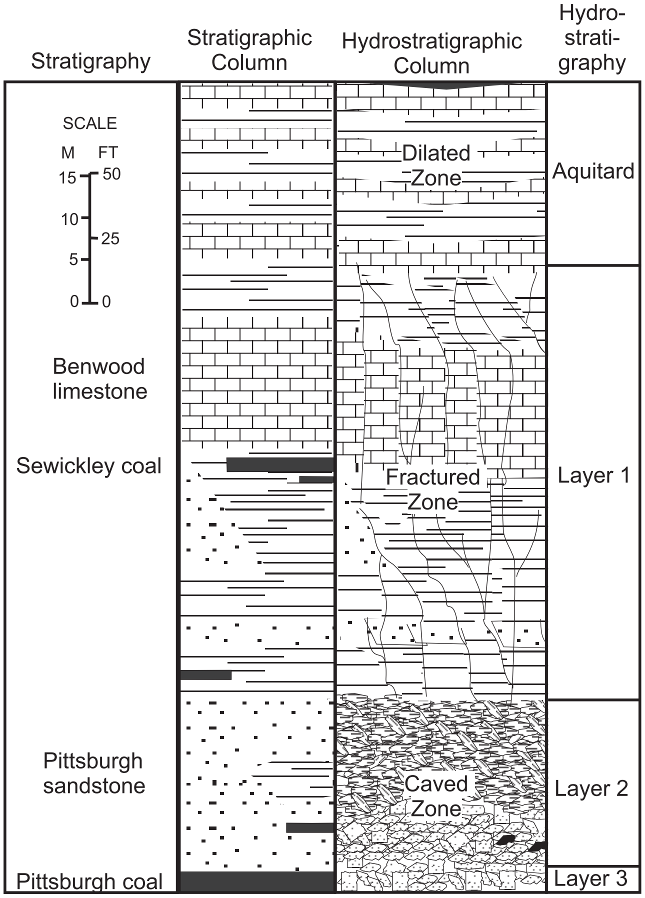

Figure 4. Generalized hydrostratigraphy of the Pittsburgh Formation, Upper Pennsylvanian Monongahela Group (after Edmunds et al., 1999). Scale is approximate.

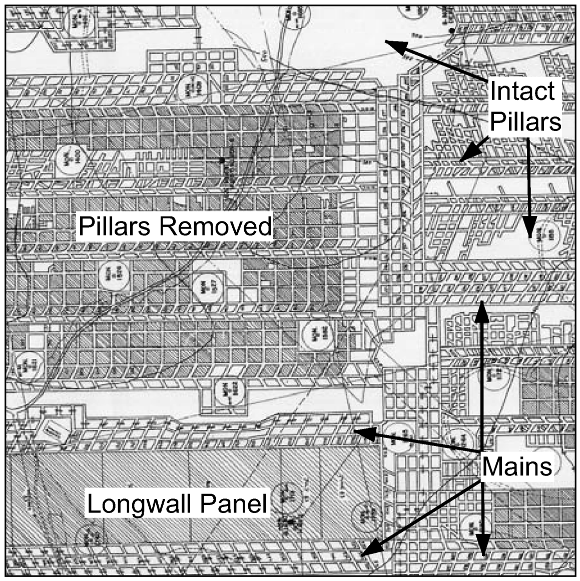

Figure 5. Plan view of typical mine map showing variation in mining methods, main entries, and un-mined coal (pillars).

within the study area. Pressures were recorded hourly and then converted to average daily water levels using a database. Three of the monitoring wells are previously existing rock-dust boreholes (GAT1, GAT2, and NEM1; Figure 2), while the other three wells (CRU1, PIT1, and MAT1; Figure 2) were all drilled for the purpose of monitoring mine-pool elevations. Historical (pre-September 2000) groundwater-elevations for the pools within Gateway and Robena (GAT1 and ROB1, respectively; Figure 2) are from unpublished file data. While limited, recent groundwater elevations for the pumped mines Dilworth and Robena (DIL1 and ROB1, respectively; Figure 2) were provided by treatment-plant operators.

Geospatial Analysis

Mine outlines and areas, inter-mine coal-barrier dimensions, and overburden isopachs for the study area were mapped using a geographic information system (GIS). Pittsburgh coal bed mine maps were obtained from the Pennsylvania Department of Environmental Protection (PADEP), digitized, and geo-rectified using mining features depicted on the maps and located in the field using a global positioning system (GPS). Inter-mine barrier segments were measured, and their areas and lengths were used to estimate average width. All barriers in the study are assumed to be 2 m high, the approximate thickness of the Pittsburgh coal in this area (Edmunds et al., 1999). The Pittsburgh coal bed structure was developed using kriged base-of-coal elevations from mine maps to create a grid. This coal-bed structure grid was subtracted from the 10 m digital elevation model (DEM) to create an overburden isopach. Because vertical infiltration rates are dependent upon overburden thickness, the latter is a factor in estimating the volume of groundwater that reaches the mine aquifer.

Fluid Mass Balance

A water budget or fluid mass balance (FMB) for mines i in the study area was developed to improve understanding of the flow regime. The FMB includes vertical infiltration (VI), extraction pumping (P), storage changes (ΔS), surface discharge (Q), and barrier leakage (L_{B}):

$$\sum_{i=0}^{n}(VI_i + L_{\mathrm{B}i} + P_i + \Delta S_i - Q_i) = 0 \qquad (1)$$

Vertical infiltration is the primary source of groundwater, while extraction pumping, surface discharge,

Table 1. *Vertical infiltration rates for regional coal mines.*

Source	Year	Coal	State	Outcrops	Average Depth (m)	*VI* (mm/d)	Method
Hawkins and Dunn	2007	LK; LF	PA	Yes		0.36	Pumping records
McDonough et al.	2005	P	PA	Yes	<18	4.65	Measured discharge
Stoertz et al.	2001	MK	OH	Yes	15	0.67	Miner's rule-of-thumb
Stoner et al.	1987	P	PA			0.45	Numeric model
Williams et al.	1993	P	PA			0.25	Numeric model
Winters and Capo	2004						
Delmont		P	PA	Yes	31	0.72	Measured discharge
Export		P	PA	Yes	37	0.59	Measured discharge
Coal Run		P	PA	Yes	37	0.46	Measured discharge
Irwin		P	PA	Yes	69	0.43	Measured discharge
Guffey		P	PA	Yes	85	0.76	Measured discharge
Marchand		P	PA	Yes	94	0.30	Measured discharge
Banning		P	PA	Yes	96	0.32	Measured discharge
McCoy	2002						
Barrackville		P	WV	No	149	0.05	Fluid mass balance
Clyde		P	PA	No	136	0.19	Fluid mass balance
Jamison #9		P	WV	No	207	0.03	Fluid mass balance
Joanne		P	WV	No	169	0.03	Fluid mass balance
Jordan		P	WV	Yes	130	0.11	Fluid mass balance
Robena		P	PA	No	174	0.04	Fluid mass balance
Shannopin		P	PA	Yes	139	0.06	Fluid mass balance
Wyatt		P	WV	Yes	101	0.21	Fluid mass balance
Overburden < 18 m*		P	PA	No	166	725	DDVIM
Overburden < 75 m*		P	PA	No	166	3.3	DDVIM

P = Pittsburgh; LK = Lower Kittaning; LF = Lower Freeport; MK = Middle Kittanning; DDVIM = depth-dependent vertical infiltration model.
*VI applied only to areas with overburden less than these thicknesses.

and addition to storage are all sinks. Barrier leakage may be a source or sink depending upon whether flow is into or out of the study area. In order to estimate mine inflow within the relatively deep mines of the study area, a depth-dependent vertical infiltration model was developed using published recharge rates for mines in the Pittsburgh coal (Table 1). The model uses a constant rate equal to the miner's rule of thumb (0.67 mm/d) of Stoertz et al. (2001) for depths from 0 to 30 m and an exponentially declining rate for depths below 30 m:

$$VI_{(d)} = VI_{(0)} \ (d \leq d_1) \tag{2}$$

$$VI_{(d)} = \varepsilon VI_{(0)} e^{-\lambda(d)} \ (d > d_1) \tag{3}$$

where $VI_{(d)}$ is the recharge rate at depth d below land surface, $VI_{(o)}$ is the maximum vertical infiltration rate in shallow aquifers, d_1 is the maximum depth at which the surface fracture and fracture zones intersect, λ is a location-specific vertical infiltration decline parameter, and ε is a fit parameter. $VI_{(o)}$ (0.67 mm/d) is similar to the vertical infiltration rate reported for unmined areas in Greene County, PA (Stoner, 1983), and roughly 40 percent of the average vertical infiltration rate for aquifers in the Monongahela River basin of northern West Virginia (Kozar and Mathes, 2001). The depth-dependent vertical infiltration model was applied to the overburden isopach, yielding a vertical infiltration estimate for the study area.

Groundwater is extracted for treatment from two mines within the study area, and there are no known surface discharges. Increases in confined storage within fully flooded areas of Gateway and Pitt Gas mines were determined using the daily average change in water-level elevation during 2012 (Figure 3) and a confined-storage coefficient estimate of 0.001. Specific yield for the small unconfined area within Pitt Gas was calculated (McCoy, 2002):

$$S_y = \frac{E_m b C_s}{\beta} \tag{4}$$

where S_y is specific yield, E_m is the coal extraction ratio, C_s is the volume of void space remaining after surface subsidence, b is the height of the coal bed, and β is the height of caved overburden. Barrier leakage estimates (L_{Bi}) were calculated using head differences between adjacent mines Δh_j, with barrier heights b; barrier segments j; barrier segment widths w_j and lengths X_j; and barrier hydraulic conductivity K_B (similar to McCoy et al., 2006):

$$L_{Bi} = \sum_{j=0}^{n} K_B b X_j \frac{\Delta h_j}{w_j} \quad (5)$$

Groundwater-Flow Model Development

Groundwater-flow modeling was applied to better understand the interactions between adjacent flooding and flooded coal mines. The goal of the model is to use groundwater-elevation heads for calibration and pumping rates at treatment plants to define the water budget. The numeric model depicts near-steady-state conditions in 2012, during which all mines in the study area except two flooding mines had attained post-flooding hydraulic equilibrium. Groundwater elevations within the two exceptions (Gateway and Pitt Gas) were within 10 m of anticipated equilibrium elevation. The pumping and water-level data available for Dilworth and Robena are from 2011, yet they are thought to be representative of average conditions in those mines, as their pool levels are maintained below control elevations and do not vary significantly from year to year, nor do the average annual pumping volumes. The flow model thus depicts average post-flooding groundwater control conditions, but it does not account for seasonal or inter-annual variability.

RESULTS

Groundwater Hydrographs

Groundwater-elevation hydrographs for the study area are shown in Figure 3. The hydrographs for Crucible and Nemacolin indicate approximate equilibrium with intra-annual fluctuations attributed to seasonal variations in vertical infiltration, precipitation, and evapotranspiration rates (Pigati and Lopez, 1999; Light, 2001), as well as barrier leakage to adjacent mines. The fact that water levels have equilibrated without surface discharge or pumping control indicates that these mines must lose water entirely to barrier leakage. Their relative increases in groundwater elevations between 2007 and 2009 are attributed to the effects of post-closure flooding in adjacent Dilworth mine, decreasing inter-mine head differences and barrier leakage from these two mines into Dilworth. Dilworth mine-pool-level control pumping began during 2008 and resulted in stabilization of the pools in Crucible and Nemacolin. The Robena hydrograph indicates that extraction pumping for managing its pool level have made it a groundwater sink for Nemacolin (Figures 2 and 3). The stable pool elevation within Mather in 2001–2002 shows the mine was only partially flooded during that period, and that any inflow from infiltration was lost by barrier leakage to adjacent Gateway and/or Dilworth (Figures 2 and 3). While water-level data are unavailable, the pool level in Mather is believed to have begun rising when the pool in Gateway reached the elevation of the barrier separating those mines. The flooding rate in Mather most likely increased following the 2004 closure of Dilworth. The pool in Dilworth is currently (2013) maintained by pumping below 225.5 m (Figure 3). A stable pool elevation prevailed in Pitt Gas prior to 2007 and was maintained by cross-barrier horizontal boreholes that were installed to drain Pitt Gas mine water into Gateway. In early 2007, the groundwater level in Gateway reached the elevation of those drains, initiating flooding within Pitt Gas. After 2007, Pitt Gas and Gateway flooded in tandem, with fluctuations in the flooding rate attributed to variation in seasonally affected vertical infiltration as well as groundwater heads in adjacent mines (Figure 3). Late in 2011, the pool elevation in Pitt Gas reached the elevation of its roof, resulting in accelerated flooding as water filled all mine voids and moved upward into low-porosity overburden fractures. In early 2013, the flooding rate continued to increase, and water levels in both mines were above the surface elevation of the Monongahela River (Figures 2 and 3). The potential for surface discharge from either Gateway or Pitt Gas at elevations above 233 m exists, as does the possibility that vertical infiltration to these mines will be entirely offset by barrier leakage to adjacent mines (similar to the case in Crucible and Nemacolin).

Geospatial Analysis

Mines in the study range from 2.3 to 80 km^2 in area, while overburden thickness varies from less than 10 m to more than 300 m, averaging 166 m (Table 2). The mines contain relatively little area with thin overburden. Less than 0.01 percent of the total area contains overburden under 18 m thick, and overburden is less than 75 m thick in only 1.5 percent of the study area (Figure 6). Pitt Gas, the smallest and shallowest mine, accounts for roughly 1 percent of the total mined area and is the only mine with overburden less than 18 m thick. Inter-mine coal barriers vary in average width from 22 to 80 m and in length from 1600 to 7600 m (Figure 2 and Table 3). The barriers separating Gateway from Mather and Nemacolin from Robena are the longest and narrowest, while the barriers separating Mather from Dilworth and

Table 2. *Mine area and overburden distribution statistics.*

Mine	Area (10^6 m^2)	Overburden Thickness (m) Min.	Max.	Avg.
Pitt Gas	2.3	8.30	153	85
Crucible	22.6	35.5	222	133
Nemacolin	39.6	49.8	240	142
Mather	19.9	77.5	265	144
Robena	79.0	31.4	328	175
Dilworth	34.1	36.4	283	177
Gateway	41.0	31.0	309	192
All mines	238	8.30	328	166

Nemacolin from Dilworth are relatively short and wide (Table 3).

Fluid Mass Balance

Initial vertical infiltration estimates were made by applying average daily extraction volumes for the pumps in Dilworth and Robena (Table 4 and Figure 2) first to mined areas with overburden less than 18 m thick (i.e., McDonough et al., 2005) and then to mined areas with overburden less than 75 m thick (i.e., Winters and Capo, 2004). Both estimates resulted in vertical infiltration rates that were considerably greater than those reported in similar studies (Table 1), indicating that vertical infiltration to deeper mined areas is a significant portion of the FMB. Published recharge rates for mines in the Pittsburgh coal (Table 1) were used to determine the form of the depth-dependent vertical infiltration model for depths below d_1 (Eq. 3; Table 5 and Figure 7). Applying the depth-dependent vertical infiltration model to the overburden isopach produced a vertical

Table 3. *Measured barrier dimensions (refer to Figure 2 for barrier locations).*

Barrier ID	Mines	Total Length (m)	Average Width (m)
C1	Crucible-Dilworth	4,395	60
C2	Crucible-Nemacolin	5,920	67
G	Gateway-Mather	6,290	22
M	Mather-Dilworth	1,600	80
N1	Nemacolin-Dilworth	2,000	61
N2	Nemacolin-Robena	7,570	36

infiltration estimate that exceeds total pumping by approximately 60 percent (Table 4). This discrepancy suggests that barrier leakage to adjacent mines outside the study area may also occur. The pool level in Clyde mine (Figure 2) was approximately 10 m above the groundwater elevation in Gateway in fall 2012, which indicates that Clyde could only act as a source, not as a sink, of barrier leakage for Gateway. Similarly, the pool in Warwick #2 is maintained by pumping at an elevation of ~230 m, well above the mine-water control elevation in Robena mine (215 m). However, both Humphrey and Shannopin mines (Figure 2) contain pools at lower elevations (157 and 190 m, respectively) than the control elevation in Robena, yet they are also separated from Robena by relatively wide barriers of limited length, and likely neither mine receives significant leakage from Robena.

Warwick #3 mine is in the Sewickley seam, about 30 m above the Pittsburgh bed, and its location straddles the barrier pillar between Robena and Shannopin mines (Figures 2 and 4). It was closed due to significant groundwater inflow through vertical fractures connecting it to the underlying Shannopin mine (Miller, 2000). The pool in Shanno-

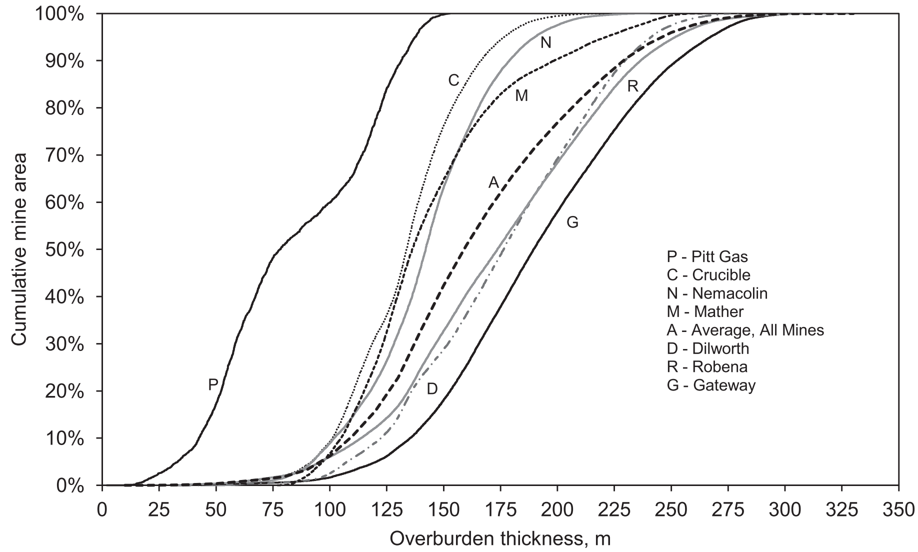

Figure 6. Cumulative distribution of mine area versus overburden thickness. See Table 2 for overburden statistics.

Table 4. *Vertical infiltration, pumping, storage, and leakage rates.*

Mine		ΔS	VI	B_L
Crucible			2,981	
C1				1,774
C2				1,207
Dilworth	−9,240		2,468	
Gateway		−471	2,284	
G				2,420
CL				0
Mather			2,247	
M				4,668
Nemacolin			4,464	
N1				416
N2				5,242
Pitt Gas		−202	725	
Robena	−2,700		5,387	
R				−7,943
Total	−11,940	−673	20,556	−7,943

All values are m^3/d; negatives offset *VI*.

pin has since been lowered by pumping to an elevation below 190 m (2012) to allow new mining in the Sewickley seam, making it a potential sink for leakage from Robena. It is interpreted that fractures between both Robena and Shannopin and the overlying Warwick #3 mine provide pathways for vertical leakage between Robena and Shannopin via the Sewickley seam workings. Any groundwater leaked into Shannopin is removed by pumping. Leakage from Robena to Shannopin via Warwick #3 is estimated thus:

$$L_W = \sum_{i=0}^{n} (VI_i + P_i + \Delta S_i) \tag{6}$$

where L_W is vertical leakage from Robena to Warwick #3 (Table 4). Estimated additions to confined storage amounted to 471 m^3/d within Gateway and 27 m^3/d in Pitt Gas, while a rate of 175 m^3/d was added to storage within the approximately 50,000 m^2 unconfined area of Pitt Gas (Tables 4 and 6). Daily pumping volumes for Dilworth and Robena were estimated by averaging annual total volumes (Table 7). Barrier leakage estimates were made for the two mines with multiple adjacent mines, Crucible and Nemacolin, assuming that the barriers are intact, homogeneous, and without hydraulically compromised areas (Table 8).

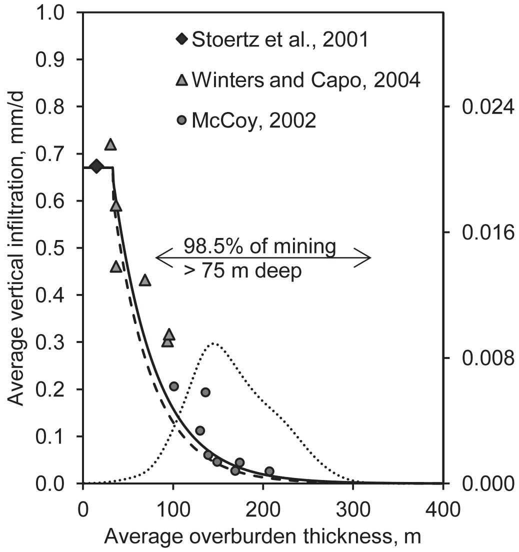

Figure 7. Estimates of groundwater vertical infiltration to underground mines, fitted using Eq. 2 and Eq. 3: $VI_{(d)} = VI_{(0)}$ ($d \leq d_1$), $VI_{(d)} = VI_{(0)}\, e^{-\lambda(d)}$ ($d > d_1$) (λ solid line and λ_{min} dashed). The density function (dotted line) describes overburden thickness for mines within the study area.

These leakage estimates suggest that groundwater in Nemacolin should leak primarily to Robena, while a small portion leaks to Dilworth. Similarly, Crucible is expected to leak most of its groundwater to Dilworth, with some going to Nemacolin.

Groundwater Flow Modeling

Data regarding coal-mine aquifers are often limited to the spatial extent of mining, sparse groundwater-head measurements, and discharge volumes, while conditions within mines and of inter-mine barrier pillars are unknown. This lack of information requires a number of assumptions in order to conceptualize groundwater flow within and between mines that comprise coal-mine aquifers. Generally, all groundwater originates as vertical infiltration downward into the mines and flows toward groundwater extraction pumps in Dilworth and Robena. Vertical infiltration is inferred to be dependent upon overburden thickness, with the highest vertical infiltration rates occurring in Pitt Gas and Robena below stream valleys, while the lowest rates occur under hills and ridges (Figure 8). Relatively small volumes of the groundwater infiltrating Pitt Gas and Gateway are assumed to be retained as storage within these mines,

Table 5. *Parameters for Equations 2 and 3.*

$VI_{(o)}$ (mm/d)	d_1 (m)	λ	ε	λ_{min}
0.67	33	0.021	2	0.023

Table 6. *Parameters for* S_y *calculations.*

β (m)	b (m)	E_m	C_s
20	2.0	0.80	0.80

Table 7. *Monthly (2011) extraction volumes for pumps in the study area (1,000 m^3).*

Mine	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Robena	260	40.9	0.68	0	175	295	216	0	0	0	0	0	988
Dilworth	250	368	303	344	300	344	407	231	0	323	249	251	3,372
Total													4,360

while the remainder leaks through the barrier between Gateway and Mather, joining vertical infiltration received by the latter mine before leaking into Dilworth through barrier segment M (Figure 9). Vertical infiltration entering Crucible leaks to both Dilworth and Nemacolin; similarly, vertical infiltration that enters Nemacolin leaks to Dilworth and Robena (Figure 8). Based on anecdotal reports by miners (Miller, 2000) and on mass balance discrepancy, some additional flow is suspected to occur upward through vertical fractures from Robena to Warwick #3 in the Sewickley seam (Figure 9). It is assumed that the Gateway/Clyde barrier (north), the east barriers of Crucible and Nemacolin (east), and the deep mining faces of Gateway and Robena (west) all are effectively no-flow boundaries. Groundwater movement to and/or from surrounding un-mined coal is assumed to be insignificant relative to other portions of the FMB. Similarly, barrier leakage between the study area and surrounding mines (Clyde, Warwick #2, Humphrey, and Shannopin) is thought to be small and have no effect on overall flow directions.

Modeling Approach

The U.S. Geological Survey (USGS) Modular Finite-Difference Flow Model (MODFLOW-2000) (Harbaugh et al., 2000) was employed to create a steady-state model of post-flooding groundwater conditions under pumping control in the year 2012. Pre- and post-processing were conducted utilizing Groundwater Vistas version 6.22. At this time, all mines in the study area except Pitt Gas and Gateway are thought to have been fully flooded and at seasonally fluctuating, but inter-annual steady state.

Table 8. *Barrier leakage estimates for mines with multiple adjacent mines (refer to Figure 2 for barrier locations).*

Barrier ID	Mines	Δh (m)	L_B (m^3/d)
C1	Crucible-Dilworth	19	223.8
C2	Crucible-Nemacolin	2.7	40.8
	Crucible total		264.5
N1	Nemacolin-Dilworth	16.3	83.4
N2	Nemacolin-Robena	24.3	801.5
	Nemacolin total		884.9

The goal of the model was to determine groundwater-flow paths and rates within and between mines in the study area.

The model employs a 100 × 100 m three-layer grid rotated 16 degrees to align with most inter-mine barriers (Figure 10). Internal coal pillars >10,000 m^2 area were also considered no-flow regions. Flow is, however, known to occur across narrow inter-mine barriers separating the mines; the magnitude and direction of this leakage were obtained by calibration using horizontal flow barrier (HFB) cells. HFB cells allow modeling of barrier thicknesses greater or less than grid spacing and variation of local barrier hydraulic conductivities K_B (Figure 10). Initial K_B values were 0.078 m/d, a value based on field calculations of McCoy et al. (2006).

All three layers are confined (LAYCON = 3) and represent groundwater flow within the mined area, as well as in overlying collapse and fracture zones, e.g., well beneath the shallow groundwater-flow system. The un-flooded portion of Robena up-dip of its water-table surface was not modeled. Vertical infiltration and barrier leakage occurring in this region were added to adjacent active cells in order to maintain the FMB.

Boundaries and Parameterization

Boundaries for the model include a recharge (vertical infiltration) boundary at the top of model layer 1, no-flow cells at the bottom of layer 3, and no-flow cells representing un-mined coal at the perimeter of the model. A single constant-head cell was located in reasonable proximity to the pumps in both Dilworth and Robena, at the elevation of the average pool control elevation maintained in these mines during 2011 (Table 9), as an aid in calibration. The constant-head cells were removed once calibration was achieved.

MODFLOW WEL-package (specified-flux) cells were utilized to simulate pumping from Dilworth and Robena; movement of groundwater into storage within nearly flooded Gateway and Pitt Gas; and upward leakage from Robena into the overlying Warwick #3 mine and, ultimately, into Shannopin to the south (Figure 10). Average daily pumping rates for Dilworth and Robena were estimated using

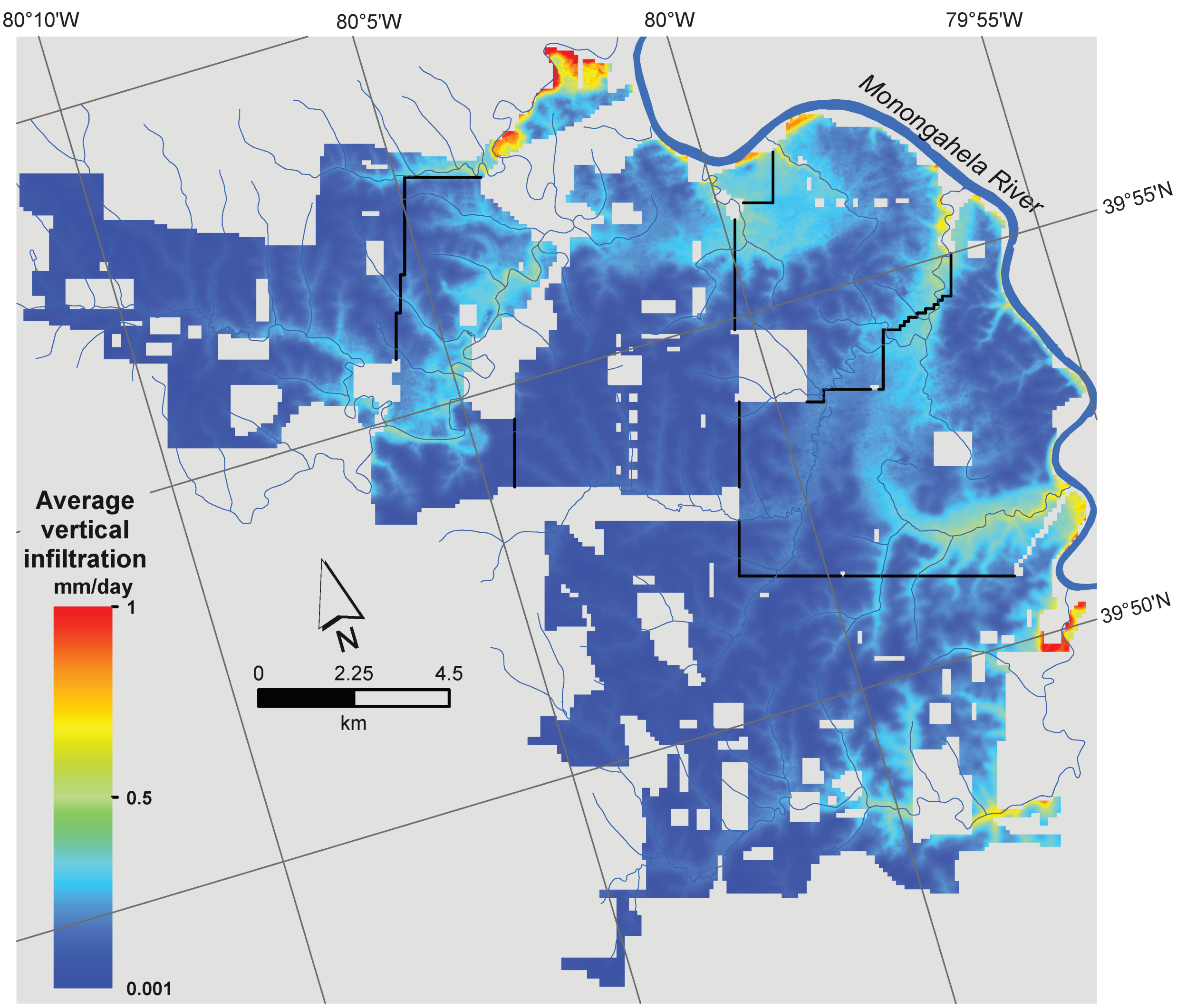

Figure 8. Vertical infiltration rates applied to the groundwater-flow model. This and later maps have been rotated from geographic north to align with the model grid.

operator-supplied values for 2011 (Table 7). The calculated daily increase in storage within Pitt Gas and Gateway was distributed across 3,951 WEL cells (Table 4 and Figure 10). Barrier leakage into Robena from Nemacolin and vertical infiltration to Robena in excess of pumping from Robena were distributed among 233 WEL cells in Robena to simulate leakage to Warwick #3 (Table 4).

Layers 2 and 3 were assigned isotropic K values of 1000 m/d to simulate large conduits associated with main entries and highly conductive gob zones. In layer 1, K_H was assigned a value of 1.0 m/d, while K_V was assigned a value of 100 m/d, reflecting the fact that layer 1 is thought to contain significant vertical fracturing.

The top of layer 1 is where groundwater enters active cells in the model by vertical infiltration. The per-cell infiltration rate was calculated at 100 × 100 m^2 grid scale using local overburden thickness and the depth-dependent vertical infiltration relationship (Figures 7 and 8).

Calibration

Although groundwater elevations vary seasonally in all these mines, average annual elevations within monitoring wells during 2012 (Table 9 and Figure 3) were used for calibration. Calibration was accomplished by iteratively adjusting K_B of individual intermine barriers until modeled heads were within 1.0 m of target values (Table 9). The calibration process also required a reduction in the volume of groundwater extracted by WEL cells for ΔS within Gateway and Pitt Gas (Table 4). A head change criterion of 10^{-5} m and mass balance error of 0.007 percent were considered sufficient for convergence.

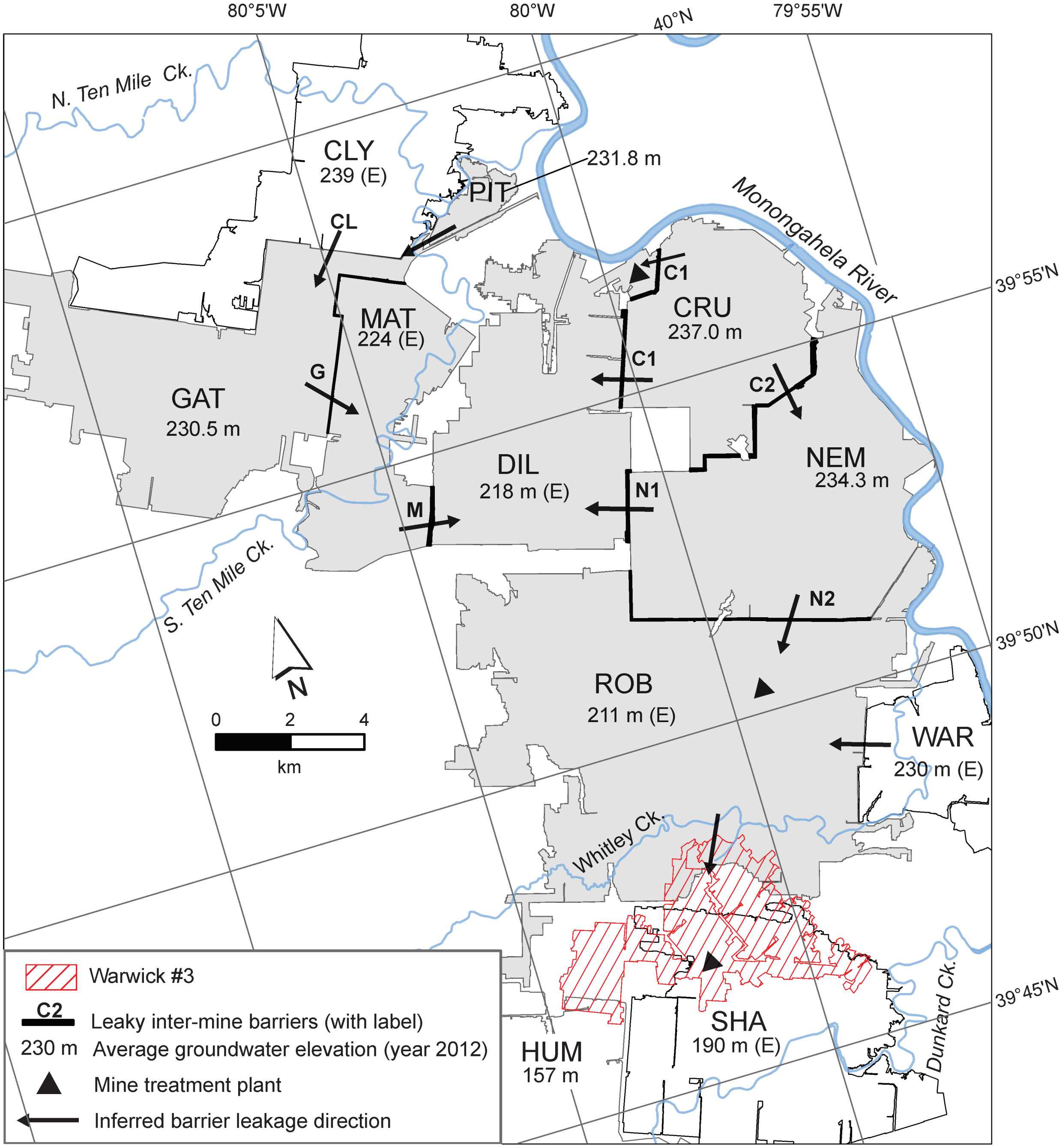

Figure 9. Conceptual model of groundwater flow across leaky barriers.

Model Results

Calibration required increasing K_B values for barrier sections by one to three orders of magnitude over initial estimates (Table 10). The calibrated potentiometric contours indicate flow within individual mines from relatively high vertical infiltration areas towards leaky barriers, pumps, and the WEL cells, which simulate leakage into the overlying Warwick #3 mine (Figure 11). These contours deflect at leaky inter-mine barriers as a result of differences in conductivity between mines and barriers. In short, the barriers tend to maintain individual pools within each mine that may receive leakage or leak into one or more adjacent mines. The potentiometric contours may be analyzed to show the locations of flow divides that partition the study area into a number of catchments, while particle traces indicate that groundwater may move through multiple mines before discharging (Figure 11).

Figure 10. Boundary condition types and locations within the groundwater-flow model. WEL cells for storage and leakage are located in layer 1; extraction wells, constant heads, and targets are all in layer 3.

DISCUSSION

Results indicate that post-mining hydrogeology within flooded and flooding underground mine complexes is amenable to numerical modeling. Known data, including groundwater elevations, mine maps, and pumping volumes, can be combined with vertical infiltration estimates to allow calculation of barrier leakage rates and flow patterns within and between adjacent mines. Results also indicate the

Table 9. *Observed and modeled groundwater-elevation heads in meters.*

Target	Min.	Max.	Avg.*	σ	Modeled
CRU	236.3	237.5	237.0	0.35	237.0
GAT1	228.0	233.4	230.5	1.46	230.6
GAT2	227.5	233.0	230.1	1.62	230.6
NEM	233.6	234.9	234.3	0.33	234.4
PIT	229.4	235.0	231.8	1.42	230.9
DIL	213.6	219.9	217.4	1.5	217.0**
ROB	209.0	213.1	211.3	1.1	211.0**

*Year 2011 for DIL and ROB, 2012 for all others.
**Values assigned to constant-head cells during initial calibration.

Table 10. *Calibrated* K_B *values.*

Inter-Mine Barrier	K (m/d)	% McCoy*
C1	0.53	700
C2	2.00	2,600
G	0.55	700
M	25.00	32,000
N1	0.30	400
N2	0.49	600

*Average K for intact coal barriers: 0.078 m/d (McCoy et al., 2006).

potential for compromised barriers with leakage rates significantly greater than would be observed due to homogeneous barrier leakage alone.

Calibrated K_B values suggest that coal barriers within the study area are more conductive than those in the Pittsburgh seam studied by McCoy et al. (2006). It is likely that these barriers are hydraulically compromised by un-mapped entries between mines, boreholes, or subsidence. The actual K_B values for intact coal barriers may well be similar to those determined by McCoy et al. (2006), but the significantly greater calibrated K_B values are the result of averaging relatively low-K_B barrier segments with relatively highly conductive compromised barrier sections. The distribution of barrier leakage out of Nemacolin and Crucible into adjacent mines indicates variation in barrier hydraulic properties and geometry. The calibrated K_B values for barriers N1 and N2 are similar (Table 10), which suggests that the significantly greater barrier leakage from Nemacolin to Robena than from Nemacolin to Dilworth (Table 4) results from the greater length and narrower width of N2 relative to N1 (Table 3), as well as the steeper head gradient between Nemacolin and Ro-

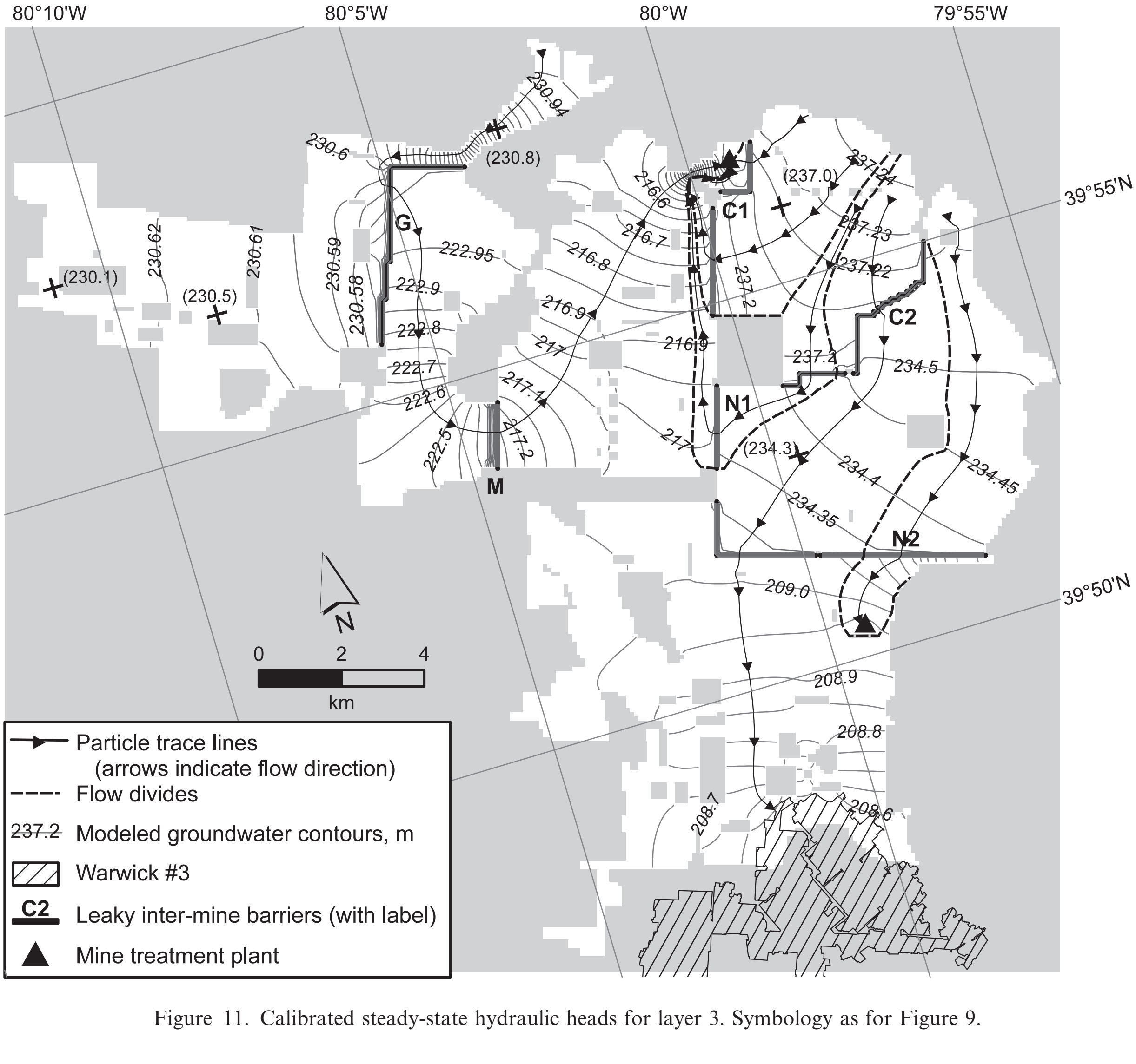

Figure 11. Calibrated steady-state hydraulic heads for layer 3. Symbology as for Figure 9.

bena (the N2 barrier) compared to Nemacolin and Dilworth (the N1 barrier; Table 9 and Figure 11). The C1 and C2 barriers are of similar width, but C2 is longer and more conductive; nevertheless, Crucible leaks more water into Dilworth than it does to Nemacolin, which suggests that the higher head gradient between Crucible and Dilworth is the primary control on barrier leakage out of Crucible (Tables 3, 4, 9, and 10). The calibrated K_B for barrier M is an order of magnitude higher than all other K_B values calculated in the model (Table 10), yet M is also the widest and shortest barrier (Table 3). These and other observations are interpreted as strong evidence that many barrier sections in this study area are hydraulically compromised and not exhibiting simple matrix or fracture flow.

Calibrated groundwater-elevation contours indicate flow toward the pumps in Dilworth and Robena and toward WEL cells in Robena, which simulate leakage to Warwick #3, and also locate several flow divides within the study area (Figure 11). The locations of the flow divides reflect variation in barrier hydraulic characteristics and geometry and outline catchments that illustrate the partitioning of groundwater between the different sinks. The catchments show that groundwater infiltrating any individual mine may flow through multiple adjacent mines before reaching a sink (Figure 11). For example, vertical infiltration entering Pitt Gas flows though Gateway, Mather, and most of Dilworth before being extracted from Dilworth, while vertical infiltration that enters Crucible may leak directly to Dilworth, leak to Nemacolin, and then to Dilworth, or leak to Nemacolin, flow through Robena, and then pass through Warwick #3 in route to pumps in Shannopin. The calibrated groundwater-elevation contours also depict relatively low head gradients within individual mines as well as significant differences between K_B and K in the collapsed zone, indicated by the deflection of contour lines near barriers. Both mimic shallow hydraulic gradients observed in underground mine pools (Aljoe and Hawkins, 1992).

The model indicates that groundwater elevations in some contiguous flooded mines may achieve seasonally varying, inter-annual equilibrium when barrier leakage from these mines to adjacent mines is sufficient to offset vertical infiltration. Crucible and Nemacolin maintain relatively constant groundwater elevations by discharging to adjacent mines. The current conditions in Mather are unknown, but groundwater elevations in that mine are similarly thought to at equilibrium as inflowing water leaks to Dilworth. During this study, Pitt Gas and Gateway were still flooding yet leaking considerable volumes of water to Mather. At present, it is uncertain whether these mines will achieve steady state by barrier leakage or ultimately discharge to the surface.

The depth-dependent vertical infiltration model yields infiltration rates that decrease exponentially with increasing depth, whereas earlier methods tended to apply uniform recharge rates to shallow areas while assuming vertical infiltration is negligible in relatively deep (>75 m) mined areas. Applying recharge only to thin overburden areas (<75 m) resulted in rates that were orders of magnitude greater than values reported for relatively shallow mines. The vertical infiltration model therefore offers an improved method when deep mining becomes a significant portion of the total mined area. Yet, there is some uncertainty in the vertical infiltration model. Within the study area, modeled vertical infiltration exceeds extraction pumping by roughly 40 percent (Table 4). The model can be adjusted to site-specific information by changing the λ value (Eq. 3). A minimum λ (λ_{min}) value was attained by setting vertical infiltration equal to pumping and additions to storage within Gateway and Pitt Gas and ignoring barrier leakage into or out of the study area, yet calibrating the groundwater-flow model to λ_{min} requires groundwater flow from Robena to Nemacolin against the head gradient. It is likely that the actual λ value is between 0.021 and 0.023 within the study area, yet further refinement of λ is considered unwarranted given uncertainties in barrier leakage rates, vertical leakage from Robena to Warwick #3, and the potential for barrier leakage between the study area and surrounding mines.

CONCLUSIONS

- Post-closure mine flooding often results in complex hydrogeological conditions among groups of adjacent mines. These conditions are influenced by vertical infiltration, barrier leakage, and pumping rates.
- The post-mining hydrogeology of mine complexes is amenable to numerical modeling given known data, including groundwater-elevation heads, pumping rates, and the geospatial extent of mining.
- Current recharge estimation for underground mines assumes that recharge only occurs in areas with relatively thin (<75 m) overburden and neglects leakage to deeper mined areas. This restriction results in increasingly high recharge rates as the depth of mining increases.
- The depth-dependent vertical infiltration model offers an improved method for estimating recharge to underground mines, especially as the area of relatively deep mined area (>75 m) increases. The model is amenable to modification for site-specific conditions in other mine complexes.

- Calibrated coal-barrier hydraulic conductivity values are greater than those reported by McCoy et al. (2006) by 3× to 25×. The causes for these increases are unknown, but it is speculated that un-mapped entries between mines, boreholes, or other conditions have resulted in hydraulic compromise of barrier integrity.
- The calibrated groundwater-flow model indicates that barrier leakage is sufficient to offset vertical infiltration within individual mines, making it possible for groundwater extraction pumps in one or more mines to control pool elevations in multiple adjacent mines. The model further indicates that vertical leakage may play a role in the FMB of mines that are overlying or underlying other mined coal seams. Vertical leakage is especially likely when the inter-burden separating mined seams lies within the fractured zone.
- The results of this study have implications for other flooding and flooded underground mines, including the post-closure treatment of mine water. Failure to consider post-flooding hydrogeological conditions such as potential inter-mine connections among adjacent mines may result in poorly sited pumps, undersized wastewater treatment plants, and underestimation of water-treatment budgets.

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