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TECHNICAL ARTICLE

Hydrologic Characteristics of a 35-Year-Old Underground Mine Pool

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Abstract The hydrology of a 14,672 acre (5,940 ha) coal mine complex in Cambria County, Pennsylvania, USA, was characterized. This flooded mine complex was evaluated to determine the potential of using the mine water for downstream agricultural purposes in an adjoining watershed. The hydrologic characteristics of the mine complex dictate the amounts and rates of mine water discharge that are available. The original coal extraction rate was known to be 63%, but post-mining subsidence has reduced the effective porosity to a mean of 11%. Thus, the mine stores considerably less mine water than was anticipated, a priori. The mine receives vertical recharge averaging 0.27 gallons (gal) per minute per acre (24.6 L/s per ha), which is equivalent to 11.6% of the mean precipitation. The recharge rate fluctuates about the mean by ±22%. The low storage capacity combined with the moderately low recharge rates allow the large mine complex to be rapidly drawn down when the pumping rate is raised from 4.68 to 9.36×10^6 gal ($17.7–35.4 \times 10^6$ L/day). Conversely, the mine refills rapidly, up to 0.8 ft (0.24 m) or spatially 33 acres (13.4 ha) per day, once the pumping rate is reduced back to 4.68×10^6 gal/day (17.7×10^6 L/day), which is well below the total recharge rate. In addition to vertical recharge, 6.3–40.4% of the inflow into the mine pool complex occurs from coal barrier seepage from an adjacent flooded mine. The seepage rates are relatively constant and are estimated to be insensitive to changes in head up to 50 ft (15.2 m).

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Introduction

As coal mining winds down in parts of the eastern United States, large abandoned underground mines are closing and are being permitted to flood. Hydrologically connected flooding mines combine to form large, high-volume mine pools that interact according to the degree of their interconnection. Recently, the discharge quality and quantity characteristics of a group of these mines has been evaluated to determine the cost of long term treatment and the feasibility of using this water for secondary industrial, agricultural, and municipal purposes. An extensive understanding of the hydrologic flow system was necessary to characterize the mine outflow and predict future behavior and mine water availability.

This paper explores and defines some methods of quantifying the hydrologic system of a large mine complex. It deals primarily with in-mine storage, and the effects of seasonal variation and high-volume pumping relative to the availability of mine water for downstream agricultural purposes during low-flow periods in the Susquehanna River basin. Rates and sources of recharge to the mine pool are also addressed. This paper only covers the quantitative portions of the larger study, which also addressed the geochemical aspects of the mine complex.

History and Background

The studied mine complex is located primarily in Cambria County Pennsylvania, near the towns of Colver, Carrolltown, and Northern Cambria (Fig. 1). Mining in this area began on the Lower Kittanning coal in the late 1880s. While some small mines remain, the last of the larger mines in the area were closed by 1986. The earliest mines were "pick and shovel" operations employing the room-and-pillar method. Much of the first mined sections were subsequently retreat mined. More recent mining was conducted primarily using the longwall method with associated room-and-pillar development. There also has been considerable room-and-pillar and longwall mining of the overlying Lower Freeport coal.

The mine complex consists of 15 large mines along with several smaller ones located along the margins near the coal outcrop. The mines were kept pumped down during the active operating phase. Lancashire 15, the deepest mine in the complex, closed in May, 1969; pumping ceased on July 14, 1969. Between March 13, 1970 and June 12, 1970, high-volume discharges of highly acidic metal-laden water developed along the northern border of the mine complex adjacent to the West Branch of the Susquehanna River (Fig. 2). The full magnitude of the discharges (blowouts) was such that the Susquehanna River experienced fish kills up to 150 miles (240 km) downstream of the discharge point. Since that time, several other mines in the basin have been abandoned and permitted to flood. These mines have merged to become part of the unified mine pool. The entire mine complex is 14,672 acres (5,940 ha), while the mine pool is somewhat smaller.

The uncontrolled discharge of the mine complex was checked by high-volume pumping from three boreholes located near the lowest point in the complex adjacent to Duman Lake Park (Fig. 2). Expansive mine drainage treatment facilities were constructed near the Duman boreholes to accommodate the huge quantities of water.

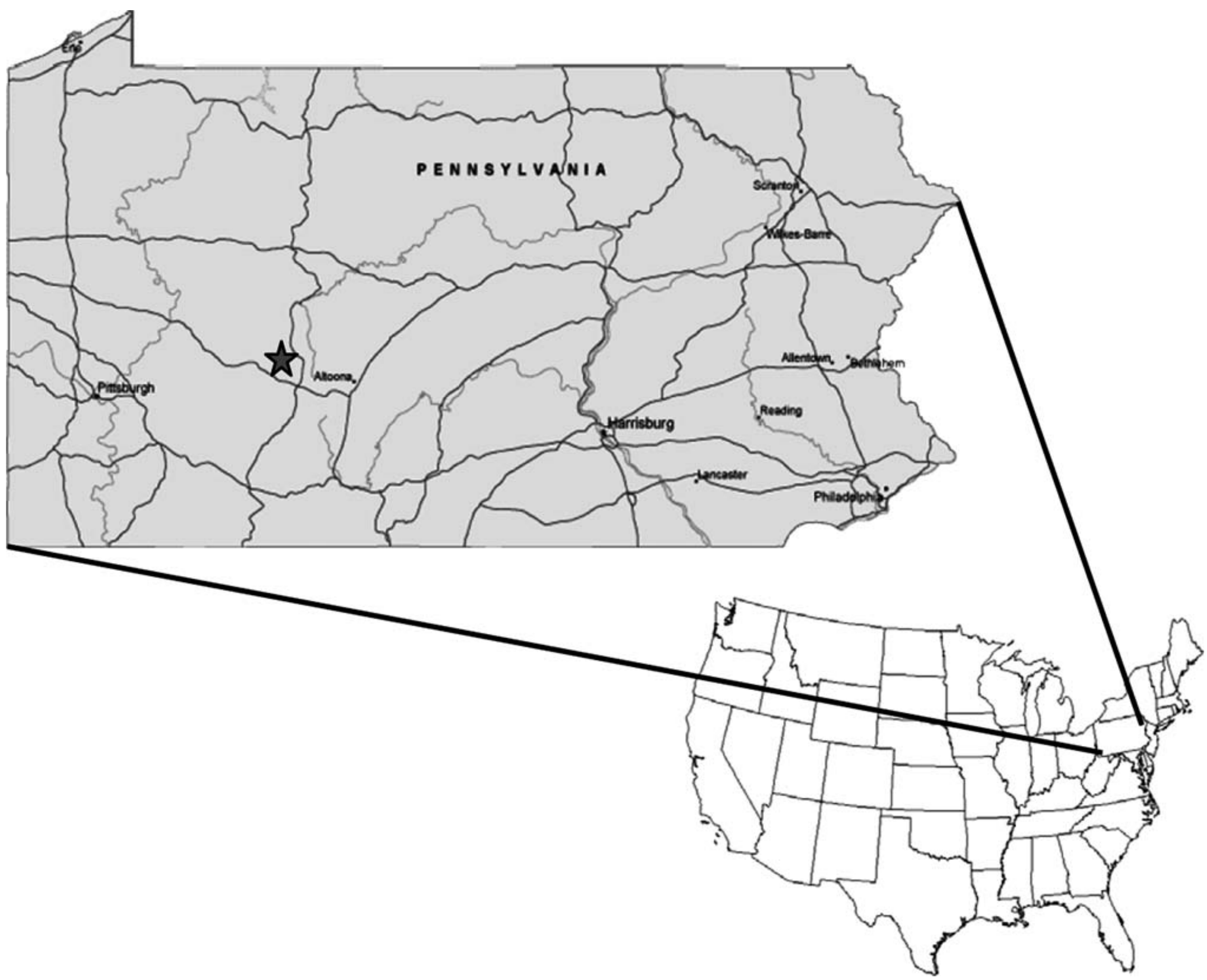


Fig. 1 General study area location map shown by the *star*

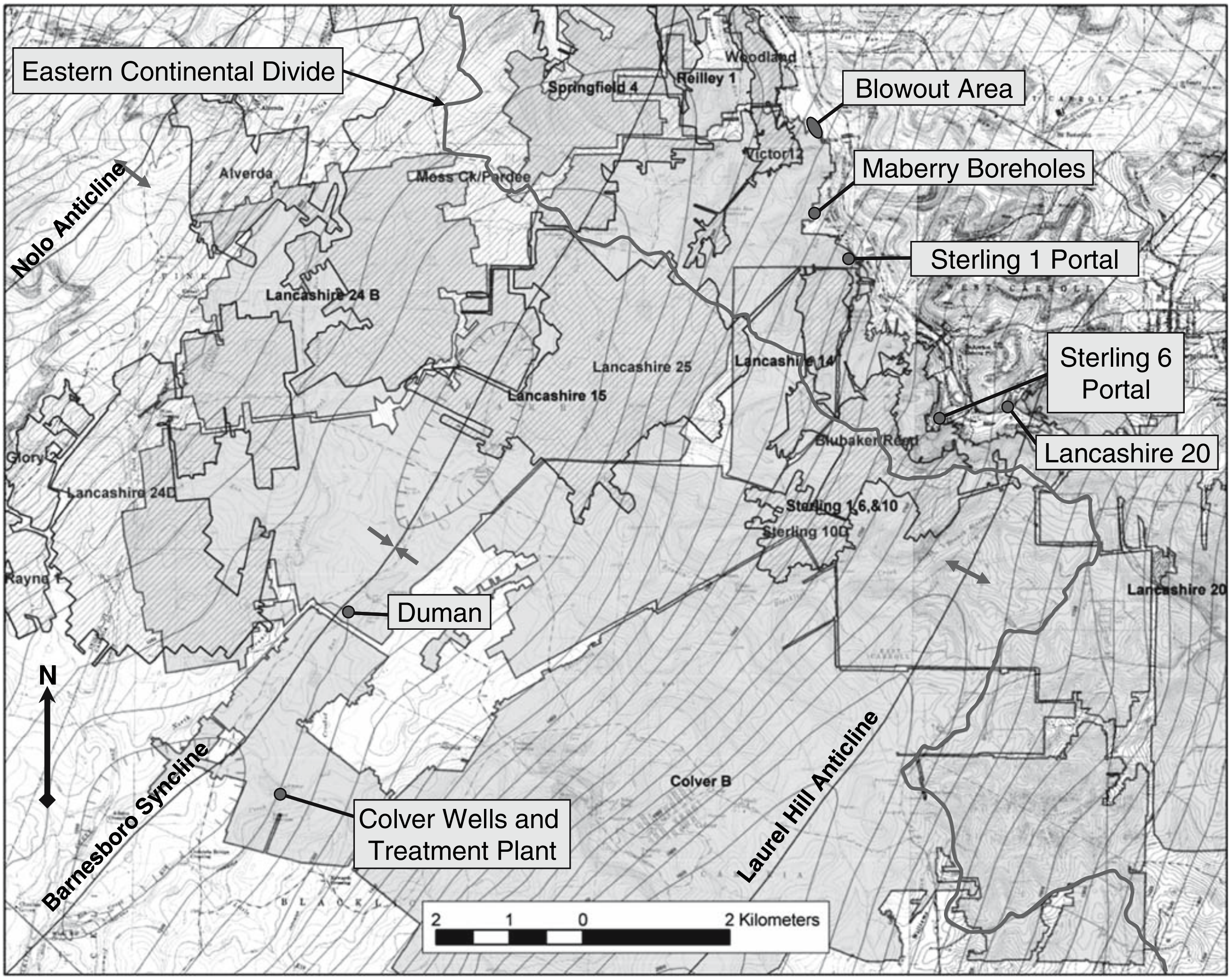


Fig. 2 Detailed study area map compiled from data created from original mine maps

Between 4.68 and 9.36 × 10^6 gal/day (17.7–35.4 × 10^6 L/day) are pumped from the mine pool, with an annual mean of 7.4 × 10^6 gal/day (28 × 10^6 L/day). After treatment, the water is discharged into a tributary of Blacklick Creek, which is in the upper reaches of the Ohio River basin. The rationale for characterizing this mine complex stems from a desire to move the treatment facilities across the Eastern Continental Divide, so that the discharging water would drain into the West Branch of the Susquehanna River, where it can be used for industrial and/or agricultural purposes downstream.

The mine complex straddles the axis of the southwest–northeast trending Barnesboro Syncline and is bounded to the east by the axis of the Laurel Hill Anticline and to the west by the axis of the Nolo Anticline (Fig. 2). The Barnesboro Syncline is a doubly plunging syncline, which creates an elongated bowl near the center of the study area. The maximum strata dip is approximately 3° along the eastern limb, with the rocks becoming essentially flat-lying approaching the synclinal axis.

The coals are associated with sandstones, interbedded with shales and a minor limestone unit near the Upper Freeport coal. The sandstones are thickest in the northeast and thin toward the southwest. The Lower Kittanning coal seam averages about 3.5 ft (1.07 m) thick, and the Lower Freeport averages 4.5 ft (1.37 m) thick. The interburden between the Lower Freeport and the Lower Kittanning averages 160 ft (49 m) thick. The overburden of the Lower Kittanning ranges from zero at the outcrop to over 640 ft (195 m) in the deeper parts of the mine complex.

Previous studies of the hydrology of the area (Gwin, Dobson and Foreman 1972; Michael Baker Jr Inc. 1978; Waite 1980) indicate that there is a high degree of interaction between several of the mines in the complex. There are open entries (pass throughs), naturally-formed fractures, and fractures created and/or accentuated by subsidence. Several normal faults with minor displacement were recorded for the adjacent, but hydrologically separate, Lancashire 20 mine (Iannacchione and Puglio 1979). These faults also provide ground water flow paths between the Lower Kittanning and Lower Freeport seams.

In this region, ground water moves from shallow aquifer zones to the underlying mines, where there is a direct hydrologic connection (Booth 1986). Booth (1984) noted a direct relationship between seasonal rainfall amounts and inflow into Lancashire 20, indicating that vertical ground water movement is significant at considerable mine depths. Fracture permeability is a cube root function of the aperture opening (Witherspoon et al. 1980); therefore, a small dilation of a fracture opening caused by subsidence will have a significant impact on the ability of fractures to transmit ground water at depth. Wahler and Associates (1979) noted that fractured zones at the Lancashire 20 mine were hydrologically connected to the surface and the largest mine inflows were related to fracture zones. These fracture zones are commonly associated with prominent stream valleys.

Mine Water Storage

Calculations were made to determine how much of the mine complex was flooded and the total volume of mine water stored, since this will dictate the amount of water available to discharge into the West Branch of the Susquehanna during low-flow periods. The mine pool water level is monitored at one of the Maberry boreholes located along the northern edge of the mine complex, approximately 5.25 miles (8.45 km) northeast of the withdraw boreholes location at Duman (Fig. 2). The water level of the mine pool varies seasonally based on precipitation and pumping rates. The mine is pumped to prevent unchecked discharges, but fluctuates over 25 ft (7.6 m) about a mean water level of 1,491 ft (454.5 m) above mean sea level (m.s.l.). At a mean water level of 1,491 ft (454.5 m) above m.s.l., approximately 79% of the mine area in the complex is flooded, producing a mine pool size of about 11,460 acres (4,640 ha).

Calculation of the storage capacity or effective porosity of the mine complex was accomplished by determining the time required for the mine to flood initially, the mean mine pool yield, and the degree of flooding at the time that the blowout occurred in 1970. The mine dewatering pumps were shut down on July 14, 1969, and the blowout reportedly occurred between March 13, 1970 and June 12, 1970, which is a time period of 242–333 days. The mean pool yield was determined from pumping records over a 16 year period. The degree of flooding was based on the size of the complex at the time of the blowout up to the spillover point of the axis of the Laurel Hill Anticline to the east.

The mean pumping rate between 1970 and 1985, prior to the additional inflow from the closure of Lancashire 24B and D mines in 1986, was 4.52 million gallons/day (mgd) (17.1×10^6 L/day). This mean pumping rate was determined from the total mean pumping rate minus the mean iron sludge injection rate (21.7% of the total pumping rate) initially after flooding. The iron sludge collected in sludge ponds during the treatment process is injected back into remote sections of the mine. There was a mean increase of 63.7% (2.88 mgd) (10.9×10^6 L/day) in the required pumping rate after Lancashire 24B and D mines closed in 1986, thus excluding data from this later period.

Calculations of the post-mining effective porosity are based on the aforementioned flooding rate and pumping data, which yield total in-mine water storage between 1.09 and 1.50×10^9 gal ($4.13–5.68 \times 10^9$ l) at the time of the blowout. At the time of the blowout, the mine pool area was calculated to be a maximum of 10,570 acres (4,278 ha), based on the mines that were abandoned at the time and maximum flooding to the lowest elevation of the Laurel Hill Anticline, which checked any further water level rise. Using the range of mine water storage, the known mining height (average 3.5 ft) (1.1 m) and the mine pool would have had an area of approximately 10,570 acres (4,278 ha) at the time it began discharging, the mean effective porosity of the mine complex was calculated at 11%. The porosity had a range between 9.0 and 12.4% about the mean. These storage volumes assume that porosity of the fractured rocks overlying the mines (estimated 0.001–0.1%) is negligible compared to the mine storage (Mackay and Cherry 1989).

The actual coal extraction volume, based on records for the mine, was determined to be about 63%. The substantial reduction in porosity illustrates that the retreat mining and longwalling caused considerable subsidence, substantially decreasing the storage capacity. A study of the mined areas indicates that up to a foot of subsidence was measured at the surface (Hershey and Meiser 2001).

With a mean water level of 1,491 ft (454.5 m) above m.s.l. and the addition of Lancashire 24B to the mine complex when abandoned in 1986, approximately 11,640 acres (4,710 ha) of mine workings are flooded. This flooded area yields a mean mine water storage for the entire mine complex of 1.46×10^9 gal (5.53×10^9 l). While this is a large volume of water, the mines theoretically would store almost six times as much or 8.36×10^9 gal (31.65×10^9 l), if the entire 63% coal extraction volume was still available for storage.

Mine Barrier Leakage

The mine complex receives a portion of recharge from mine water seepage through a common barrier from the

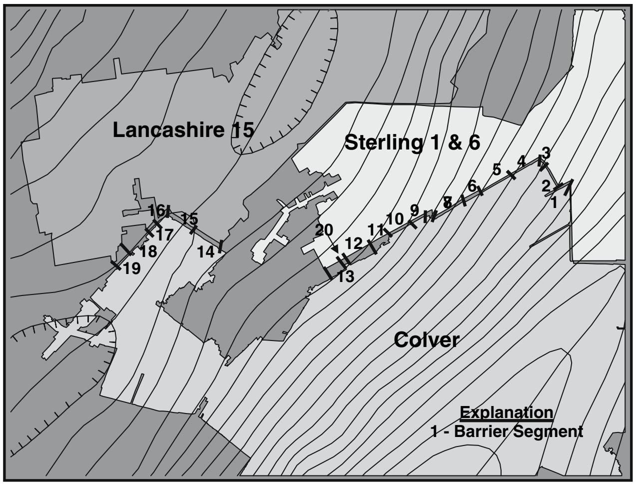


Fig. 3 Saturated coal barrier between the Colver, Lancashire 15, and Sterling 1 and Sterling 6 mines

Colver mine. The coal barrier that separates the two mines runs approximately 44,900 ft (13,690 m), excluding areas where large blocks of unmined coal essentially preclude mine water movement. Of the entire barrier, 25,760 ft (7,852 m) includes flooded portions of Colver. The coal barrier thickness ranges from 31 to over 1,500 ft (99.45–457 m). The intact barrier prevents open channel or free flow of mine waters to the mine complex from Colver, but does permit a certain amount of seepage.

A series of calculations were conducted to estimate the contribution (seepage) of the Colver mine to the mine complex. Seepage calculations used the Darcian flow equation, water levels in the mine complex and Colver, and coal barrier dimensions (height, width, and thickness). The barrier was separated into 20 segments with an average thickness determined for each segment based on 10 or more equally spaced measurements along that segment (Fig. 3). The minimum mean head difference (231.2 ft) (70.5 m) was determined from the mean water elevation for the mine complex as measured at the Maberry borehole (1,490.76 ft (454.5 m) above m.s.l.), subtracted from the mean water elevation in the Colver mine [1,722 ft (525 m) above m.s.l.]. The head values for the unflooded sections of Sterling 1 and 6 portions of the mine complex that are up gradient of the flooded sections are based on the mine floor structure contours. Hydraulic conductivity values for the Lower Kittanning (PADEP, unpublished), obtained from previous testing in the area, were used in seepage calculations. Minimum, median, and maximum hydraulic conductivity (K) values of 5.61×10^{-5}, 8.66×10^{-6}, and 6.30×10^{-8} ft/s (1.71×10^{-5}, 2.64×10^{-6}, and 1.92×10^{-8} m/s), respectively, were employed in a series of calculations for the final seepage estimates.

The head difference between the two mines (>230 ft or 70 m) indicates that the barrier is completely intact (e.g. no open pass throughs). However, the overall barrier may have an average hydraulic conductivity value higher than expected for coal at depth in this region.

Seepage estimates for present head conditions using the median K value indicate that a mean of 320 gpm (72,600 L/s) is entering the mine complex through the barrier from the Colver mine (Table 1). This flow rate is 6.3% of the mean total discharge from the mine complex and shows that the Colver mine is a substantial contributor to the discharge at the Duman treatment plant. However, these calculations are likely conservative because they are based on a median K value for the solid coal alone. The known subsidence from the high coal extraction rates of both mines has caused substantial fracturing of the overburden, which, given the elevated water levels in the two mines, is undoubtedly transmitting mine water over the barrier as well. Mining-induced stresses will also cause increased fracturing, hence permeability, in the coal itself. Analysis of the overall hydrologic system indicates that the true seepage rate between the two mines is somewhat higher than that estimated using the median K. The seepage rate [2,072 gpm (470,580 L/s) or 40.4% of the total discharge] calculated with the highest K value is, based on empirical data, indicated to be too high. Therefore, the actual barrier seepage is between the seepage rates determined using the median and highest K values. Additionally, it is highly likely, based on experience with area mines, that the barrier thicknesses in some mine sections are thinner than shown on the final mine maps.

Table 1 Summary of Colver seepage contribution to the Duman discharge under various head differentials and hydraulic conductivity (K) values

Drawdown of the mine complex (ft)	Low flow (% of total recharge)	High flow (% of total recharge)	Avg. flow (% of total recharge)	Lowest K value (gpm)	Median K value (gpm)	Highest K value (gpm)
0	10.1	5.0	6.3	2.3	320	2,072
10	10.3	5.2	6.4	2.4	327	2,121
20	10.6	5.3	6.6	2.4	335	2,167
30	10.8	5.4	6.7	2.5	342	2,213
40	11.0	5.5	6.8	2.5	348	2,252
50	11.2	5.6	7.0	2.6	354	2,294

A series of increasing-head calculations were conducted to estimate the effect of increased drawdown in the mine complex on barrier seepage. These calculations were performed to simulate additional drawdown of the mine pool that may occur when additional water is needed for the Susquehanna River. Table 1 illustrates, as expected, that seepage from the Colver mine increases as head differential increases. However, the seepage rate increases are gradual and not highly sensitive to increasing head differential up to 50 ft (15.2 m). The seepage contribution of the Colver mine to the discharge at Duman using the median K value is at least 320 gpm (72,600 L/s) (6.3%) presently, and may increase to a total of 354 gpm (80,400 L/s) (7.0%) if the drawdown is increased by 50 ft (15.2 m). Employing the highest K value under present head conditions, the Colver contribution increases to 2,072 gpm (470,580 L/s) or 40.4% of the total discharge rate. With a 50 ft (15.2 m) increase in drawdown in the mine complex, the seepage is estimated at 2,294 gpm (521,040 L/s) or 44.7% of the total discharge. Both sets of calculations illustrate that the seepage rate is relatively insensitive to changes in head. The substantial changes in the seepage rate using different K values indicate that the coal transmissive properties are a main controlling parameter of the barrier seepage. A better approximation of the median and range of K values along the entire barrier is needed to narrow the range of barrier seepage rate estimates and thus the Colver contribution to the Duman pumping rate.

At the current water level of 1,722 ft (525 m) above m.s.l., about 57.4% of the Colver mine on the west side of the Laurel Hill Anticline is completely flooded. The remainder is unflooded and recharging waters drain freely west toward the flooded portions (Fig. 2). The bulk of the outflow from the Colver mine is from two large diameter flowing artesian wells that yield a mean of 3.54 mgd (13.4×10^6 L/day). The rest of the mine water exits the Colver mine through the common barrier with Lancashire 15, and Sterling 1 and Sterling 6.

Determination and Characterization of Recharge

The total inflow into the complex plays a pivotal role in mine water availability. Recharge rate for the entire mine complex varies seasonally about a moderately low average. Inflow from flooded adjacent mines remains relatively consistent throughout the year, whereas vertical recharge varies with precipitation. The mean precipitation for the area is approximately 45 in. (114 cm) per year or 2.32 gpm/acre (213 L/s per ha).

Since 1986, when the Lancashire 24B and D mines closed, the mine complex has had a mean discharge (recharge) rate of 7.4×10^6 gal (28×10^6 l)/day. The present total mine complex area is approximately 14,672 acres (5,940 ha). This area yields a mean overall recharge rate of 0.35 gpm/acre (32.4 L/s per ha). However, the mine complex receives lateral inflow (barrier seepage) from at least one adjacent flooded underground mine (Colver mine). The estimated inflow from Colver is broad, between 320 and 2,072 gal (1,210–7,843 l) per minute or 6.3–40.4% of the total discharge from the mine complex. When this inflow rate is subtracted from the total discharge, the mean recharge rate for the entire mine complex is determined to be between 0.21 and 0.33 gpm/acre (19.2 and 30.6 L/s per ha) (mean 0.27 gpm/acre) (24.6 L/s per ha) or 9.1–14.2% of the mean annual precipitation rate.

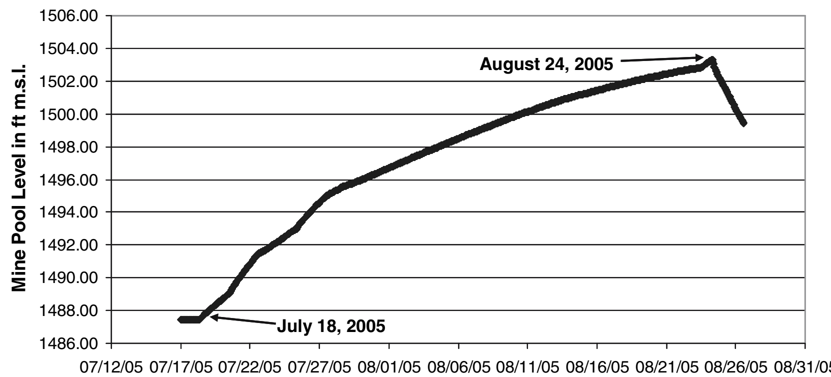
The mean recharge rate for the openly interconnected Lancashire 24B and D mines, calculated from its additional contribution to the ultimate discharge, is 0.75 gpm/acre (69 L/s per ha). This value is similar to those recorded by Hiortdahl (1988) and the U.S. EPA (1975). However, a portion of an adjacent mine, Moss Creek, appears to drain into the Lancashire 24B, greatly augmenting its flow (Waite 1980). The higher recharge rates of Lancashire 24B and D are also related to the shallower cover over the Lower Freeport seam mining and the longwall mining that occurred. The recharge rates given by Booth (1984) for the nearby Lancashire 20, higher than normally expected (1.16–2.12 gpm/acre) (106.8–195 L/s per ha), also appear to be related to the high percentage of longwall mining and the shallower cover over much of the mine.

The mine complex recharge rate range calculated during acute low-flow conditions (July 18 through Aug. 24, 2005) dropped to 0.13–0.25 gpm/acre (12–22.8 L/s per ha) with a mean of 0.19 gpm/acre (17.4 L/s per ha). The rate of mine pool rise for this period, measured at the Maberry boreholes, is shown on Fig. 4. This recharge estimate was determined during a period of "moderate drought" (−2.0 to −2.9) using the modified Palmer Drought Severity Index (which is unitless) (Heddinghaus and Sabol 1991; Palmer 1965). A second recharge rate range calculated during low flow (May 21 and June 17, 2005) was 0.15–0.27 gpm/acre (13.8–24.6 L/s per ha) with a mean of 0.21 gpm/acre (19.2 L/s per ha). Both determinations included subtraction of the barrier seepage contribution of the Colver mine.

Mean recharge of the mine complex during high flow conditions was estimated during a period (July 1 to July 31, 2004) when the modified Palmer Drought Severity Index ranged between "Unusual Moist Spell" (+2.0 to +2.9) to "Extremely Moist" (+4.0 or greater) (Heddinghaus and Sabol 1991; Palmer 1965). The recharge rate range for that time period was calculated at 0.28–0.40 gpm/acre (25.8–36.6 L/s per ha) with a mean 0.34 gpm/acre (31.2 L/s per ha), excluding the barrier seepage from Colver. Figure 5 shows the rate of mine pool drawdown during this period.

The entire mine complex yields a range of 4.4–6.9 mgd ($16.7–26.1 \times 10^6$ L/day) from direct vertical recharge to the

Fig. 4 Low-flow recharge period hydrograph with one pump operating



system. An additional 0.46–3.0 mgd (1.74–11.35 × 10^6 L/day) enters the pool via barrier seepage from the adjacent Colver mine, yielding a mean total of 7.4 mgd (28 × 10^6 L/day). Under low-flow, the combined direct recharge and barrier seepage to the mine complex is approximately 5.6 mgd (21.2 × 10^6 L/day) or 76% of the mean rate. The mine complex has yielded 7.6 mgd (28.8 × 10^6 L/day) from vertical recharge for a total 8.8 mgd (33.3 × 10^6 L/day) under high flow conditions, including coal barrier seepage, which is about 19% above the mean.

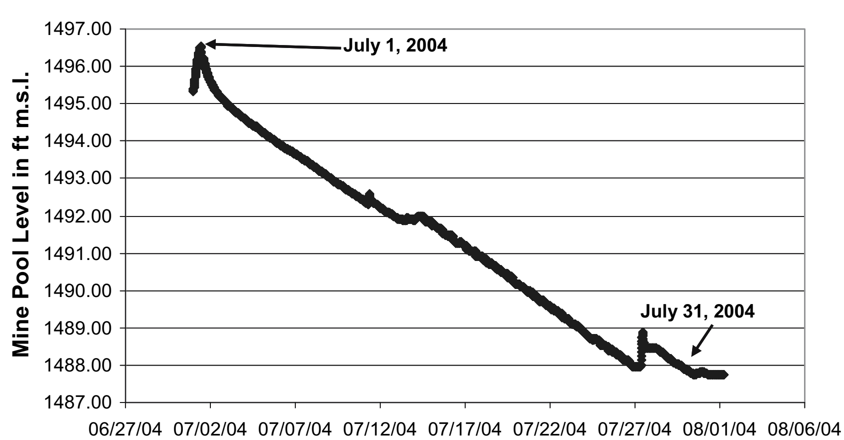
Water Level Responses to Precipitation Events

The mine pool level responds rapidly to precipitation. Precipitation data from the nearby Ebensburg, PA weather station were compiled and compared to changes in water levels recorded at the Maberry Borehole. Based on records of several rainfall events, the median lag time between a significant event and a response (rise) in water level in the mine complex is 3 days. The response lag times ranged from 2 to 5 days depending on the preceding climatic conditions. Figure 6 is an example of 3-day lag in the mine pool level response to a 0.81 in. (2.1 cm) rain event followed by a 0.59 in. (1.5 cm) rain.

Depending on the amount of precipitation and antecedent weather conditions, the mine pool response can be significant, even with two pumps operating. Water level rises exceeding 2 ft (0.61 m) within 3 days of a significant rainfall have been recorded for the mine pool. For example, the mine pool level rose from 1,490.92 ft (454.4 m) to 1,492.94 (455.0 m) between May 22 and May 25, 2004 from preceding precipitation of 4.27 in. or 10.8 cm that occurred from May 18 through 22, 2004.

The quick and distinct response of the mine pool to precipitation illustrates the close link of the mine-pool complex and shallow ground-water and surface-water systems. Booth (1984) observed a similar relationship for the Lancashire 20 mine. Extensive stress-relief fracturing in shallow cover areas [about 200 ft (61 m) or less] in this region facilitate much of the mine recharge (Ferguson 1967; Wyrick and Borchers 1981). Linear fracture zones, associated with photo lineaments and principal valleys, permit discrete recharge to mines at greater depths (Booth 1984; Tyrna and Phillipson 2001). This close relationship to shallow water systems, low storage capacity of the mine-pool, and quick response to pumping rate changes, causes the rapid water level changes. For example, mine pool rises of more than 24 ft (>7.32 m) over a 31 day period have been recorded. Experience with mine complexes of this

Fig. 5 High-flow recharge period hydrograph with two pumps operating



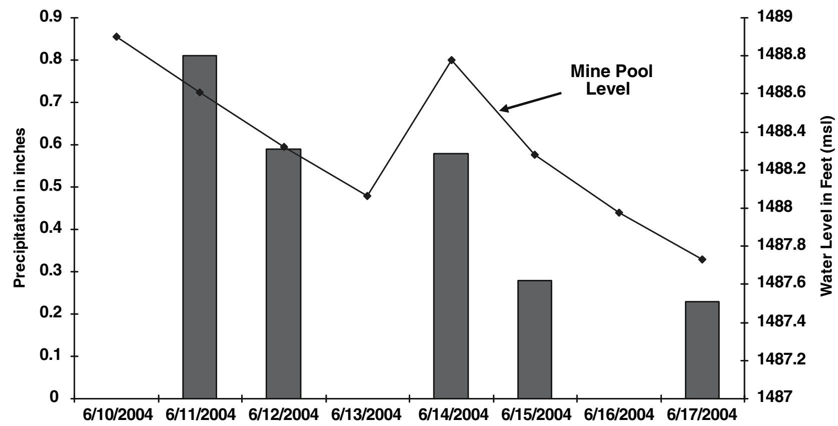


Fig. 6 Example of water-level response of the mine pool to precipitation measured at Ebensburg, PA

size in this region, indicate that pool level changes of that magnitude are unusual.

Mine Water Pumping

The relatively low effective porosity and moderate to low mean recharge rate causes the mine pool level to respond rapidly and substantially to changes in the pumping rate and to significant precipitation events. The pumping rate has the greatest influence on the pool level. Figure 7 illustrates the rapid rise and fall of the mine pool levels in response to operating two pumps (pumping 9.36 mgd or 35.4×10^6 L/day) and only running one pump (pumping 4.68 mgd or 17.7×10^6 L/day), respectively. The portions of the graph where it is flat-lined are times when the mine pool level dropped below the bottom of the monitoring well.

The mine pool behaves fundamentally as a single confined or semi-confined aquifer. The up-gradient unflooded sections of the mine are freely connected to open portals in Sterling 1 and 6 (Map 2), thus causing the mine pool to behave more as a semi-confined aquifer. This mine pool characteristic is illustrated by the response to switching over from one operating pump to two. The mine water level measured at the Maberry borehole, over 5 miles (8 km) north of the Duman pumping wells, begins to lower almost instantaneously. The mine water level reaction at Maberry borehole occurred within the measurement interval of the water level data logger for the mine pool, which was every 15 min. The free interconnectedness of the mines comprising the mine pool between those two points is attested to by this immediate reaction to pumping changes.

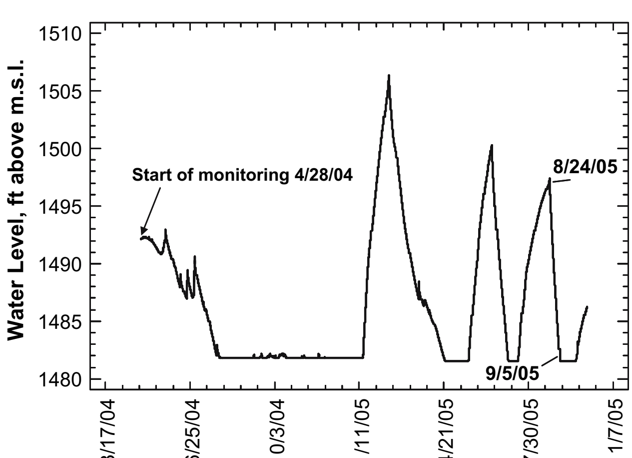


Fig. 7 Hydrograph of the mine pool measured at the Maberry boreholes

Several domestic and public water wells in the region that terminate just above the Lower Kittanning mines, but within the range of mine pool fluctuation, also illustrate that the mine pool behaves as a confined or semi-confined aquifer. These wells exhibit no noticeable impacts of mine water when the mine pool level rises well above the bottom of these wells. The mine pool was not directly breached, and thus exhibits little upward flow under moderate piezometric pressures in the deeper parts of the basin where fracturing of the overlying strata is minimal.

As previously stated, when two pumps are operating, the water level begins to recede immediately. The rate of decline depends on the antecedent climatic conditions (i.e. high recharge verses low recharge periods). During periods of high recharge, such as July 1 to July 31, 2004, the rate of mine pool drawdown was measured as low as 0.26 ft/day (0.08 m/day) (Fig. 5). However, the drawdown rate during low recharge periods can be nearly five times as fast. The drawdown during the period of Aug. 24 to Sept. 5, 2005 was estimated at 1.25 ft/day (0.38 m/day) (Fig. 7).

The rapid dewatering of the mine due to high-volume pumping occurs because once the total recharge rate is exceeded, all of the remaining pumped water is removed directly from storage. Including lateral inflow, the mine complex yields 7.4 mgd (28×10^6 L/day) during periods of average recharge. If the pumping rate is 9.36 mgd

(35.4×10^6 L/day), roughly 2 mgd (7.6×10^6 L/day) are removed from storage. The mine complex stores approximately 125,500 gal per acre (192,250 L/ha) on average. Removal of 2 mgd (4.6×10^6 L/day) is equivalent to dewatering nearly 16 acres (6.5 ha) per day under average conditions. During low-flow, the total recharge rate is 5.6 mgd (21.2×10^6 L/day), which causes the dewatering rate to increase to 30 acres (12.1 ha) per day or 1.4% of the entire mine complex in 1 week. The rate of dewatering during high-recharge periods decreases to 4.5 acres (1.8 ha) per day.

Conversely with one pump running, the water level rises rapidly because the withdrawal rate is greatly exceeded by the recharge rate. This is true even during low-flow periods. When one pump is operating, the mine water extraction rate is approximately 4.68 mgd (17.7×10^6 L/day). Recovery rates up to 0.8 ft (0.24 m) per day have been recorded during these periods. The rate of mine reflooding under average recharge is approximately 22 acres (8.9 ha) per day. The area of mine reflooded under low and high-recharge conditions has been recorded at 7.3 and 32.8 acres (2.95 and 13.27 ha) per day, respectively. During high-recharge conditions and with one pump operating, roughly 1.6% of the entire mine complex could be reflooded in a week.

Discussion and Conclusions

Actual storage capacity and effective porosity of abandoned underground mines can be significantly lower than that estimated from the coal extraction percentages. Substantial subsidence associated with high-extraction mining (e.g. retreat and longwall mining) causes the available void volume to be diminished. In the study site, the effective porosity was reduced from the original 63% extraction volume to approximately 11% (an 83% reduction).

The mean total recharge for the mine complex is 0.35 gpm/acre (0.55 L/ha). The mean vertical recharge rate (excluding barrier seepage) is between 0.21 and 0.33 gpm/acre (0.32 and 0.51 L/ha). Recharge rates ranged about 20% above and below the mean during high- and low-precipitation periods, respectively. Adjacent mined areas exhibit substantially higher recharge rates due to changes in mining methods and overburden depth. The thicker cover over much of the mine complex, compared to adjacent mines, contributes to its lower recharge rates. Lateral recharge via barrier seepage from an adjacent flooded mine is estimated at no less than 6.3% and no more than 40.4% of the total discharge.

Due to the relatively low storage capacity and moderate to low recharge rates, high-volume pumping from the mine complex causes rapid lowering of the mine pool levels. During high-recharge periods, pumping the mine at 9.36 mgd (35.4×10^6 L/day) can lower the water level at 0.26 ft/day (0.08 m/day). During low-recharge periods, the mine pool can fall as much as 1.25 feet/day (0.38 m/day). Depending on the mine complex recharge rate, a pumping rate of 9.36 mgd (35.4×10^6 L/day) causes dewatering at a range of 4.5–30 acres (1.82–12.1 ha) per day, with a mean of 16 acres (6.47 ha) per day. Operating only one pump allows rehydration of the mine at rates of 0.8 ft (0.24 m) per day, which equals up to 33 acres (13.4 ha) per day. The low storage capacity also facilitates rapid but short duration rises in water levels in response to significant precipitation events.

The mine pool acts as a confined or, more likely, a semi-confined aquifer that reacts immediately to changes in the pumping rate across long distances. Sections of the mine under piezometric pressure exhibit little upward flow. However, shallow cover area recharge zones that are openly connected to the system via stress-relief fractures and prominent linear fracture zones allow discrete recharge from shallow aquifers to greater depths. The open hydrologic connection to the mine is illustrated by pool level responses (rises) to significant precipitation events, which generally take from 2 to 5 days. It is possible that some of the water level change is due to barometric changes associated with the precipitation events, but the openness to the mine complex at portals for Sterling 1 and 6 (Fig. 2) and the lag time for the water-level response indicate that the precipitation infiltration is the main cause.

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