

## GROUND-WATER FLOW AND QUALITY IN A FULLY FLOODED UNDERGROUND COMPLEX<sup>1</sup>

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**Abstract** Water quantity and quality conditions are described for a mine-pool aquifer in a fully flooded complex of underground mines in northern West Virginia. Abandoned mines in the Pittsburgh coal bed are contiguous, and separated by coal barrier pillars ranging from as little as 9 to about 60 meters thick. Barrier pillars are transmissive enough to circulate significant quantities of water between mines, yet they control head distribution and flow direction within the aquifer. The mine-pool acts as a partly confined to confined aquifer, and recharge is approximately balanced by withdrawal of about 5700 Liters/minute, leakage to adjacent mines, and unquantified outflow to unmined areas. Resulting drawdown prevents the mine-pool from discharging directly into overlying streams. A centrally located subgroup of mines within the aquifer currently acts as a ground-water sink, but water levels are slowly increasing in the sink, and in some outflow areas. Mine waters are highly reduced, with circumneutral pH, and variable Fe concentrations from 5 to over 100 mg/L. Total alkalinity averages about 200 mg/L with a mixed Ca-Na-HCO<sub>3</sub>-SO<sub>4</sub> composition in recharge areas. End of flow path waters contain up to 600 mg/L alkalinity, and are Na-SO<sub>4</sub> type waters with higher dissolved solids and metals concentrations. The shift from Ca to Na dominated waters is attributed mainly to cation exchange. Potentiometric head is increasing in the aquifer, and mine-pool withdrawal may have to be increased to prevent discharge to the surface. Mine-pool quality remains poor, and has shown slow improvement in 6 years of monitoring.

Additional Key Words: barrier pillar, leakage, confined aquifer, cation exchange

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<sup>1</sup>Paper was presented at the 2004 National meeting of the American Society of Mining and Reclamation and the 25<sup>th</sup> West Virginia Surface Mine Drainage Task Force, April 18-24, 2004. Published by ASMR, 3134 Montavesta Rd., Lexington KY 40502

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Proceedings America Society of Mining and Reclamation, 2004 pp 1460-1478

DOI: 10.21000/JASMR04011460

<https://doi.org/10.21000/JASMR04011460>

## **Introduction**

Underground mining in the Pittsburgh coal bed of northern Appalachia has been ongoing for over 200 years. Of the original estimated reserves of about 31 billion tonnes, about 14 billion tonnes remain, and Pittsburgh seam production remains the largest in northern Appalachia (Ruppert et al, 1999). Many of the Pittsburgh seam mines are aerially extensive, covering several thousand hectares (ha), and they frequently adjoin other mines in the same coal bed. When these mines are closed and abandoned, ground-water infiltrates from overlying aquifers, stream leakage and adjacent flooded mines. The flooding process usually occurs over a period of years to a few decades. Flooding may be complete or partial, depending on hydrological setting. Mine water quality ranges from strongly acidic to alkaline, with objectionable concentrations of Fe and SO<sub>4</sub>. This paper reports on ground-water flow, storage, and quality characteristics of a fully flooded mine-pool near Fairmont, West Virginia, gathered from five years of monitoring.

## **Background**

### **Geologic Setting**

The Pittsburgh coal bed is present over portions of the states of PA, WV, MD and OH, extending over about 28,000 square kilometers (km<sup>2</sup>) (McCullogh et al, 1975; Ruppert et al, 1999), (Fig. 1). The coal bed is in an elongated basin with the main axis extending southwest to northeast. A series of small anticlines and synclines is superimposed on the main basin structure. Deformation, including folding, and regional uplift facilitated erosion of some of the original deposit. Throughout much of the basin, the coal bed is located at depths of 60 to greater than 300 meters (m), but is at or near outcrop along basin margins.

Stratigraphically, the Pittsburgh is located at the base of the Monongahela Group, which ranges from about 70 to 130 meters in thickness (McCullogh et al; 1975, Berryhill et al, 1971; Hennen and Reger, 1913). The lower members of the Group include several limestones, calcareous shales and mudstones, interbedded with fine to medium grained sandstones. The coal bed itself is 2 to 3 meters thick and characteristically is divided into several benches (Hennen and Reger, 1913).

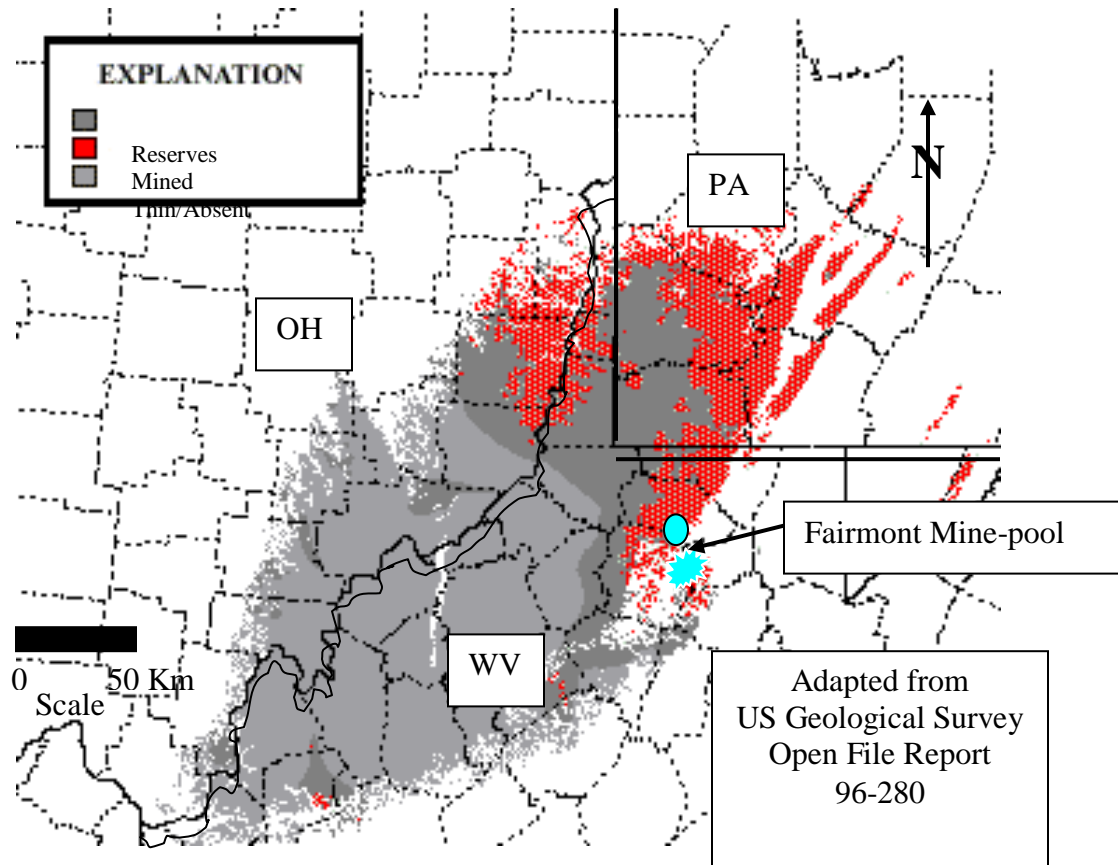


Figure 1. Extent of Pittsburgh coal bed and location of Fairmont mine-pool. (Adapted from Ruppert and Tewalt,1997).

### Project Setting

A complex of abandoned, fully flooded underground mines, termed the ‘Fairmont mine-pool’ in this paper, has been monitored by the Office of Surface Mining (OSM) since the mid 1990’s. The Fairmont mine-pool is located on the eastern margin of the basin (Fig. 1) and the rocks dip at a low angle to the northwest toward the center of the basin. This structure results in the Pittsburgh coal cropping out or being present at shallow depths along the West Fork and Monongahela Rivers near Fairmont. The rivers and tributaries are potential discharge zones for the mine-pool.

Fig. 2 shows the location of principal underground mines comprising the Fairmont mine-pool and several adjacent mines that interact with it. The mine-pool extends over about 10,000

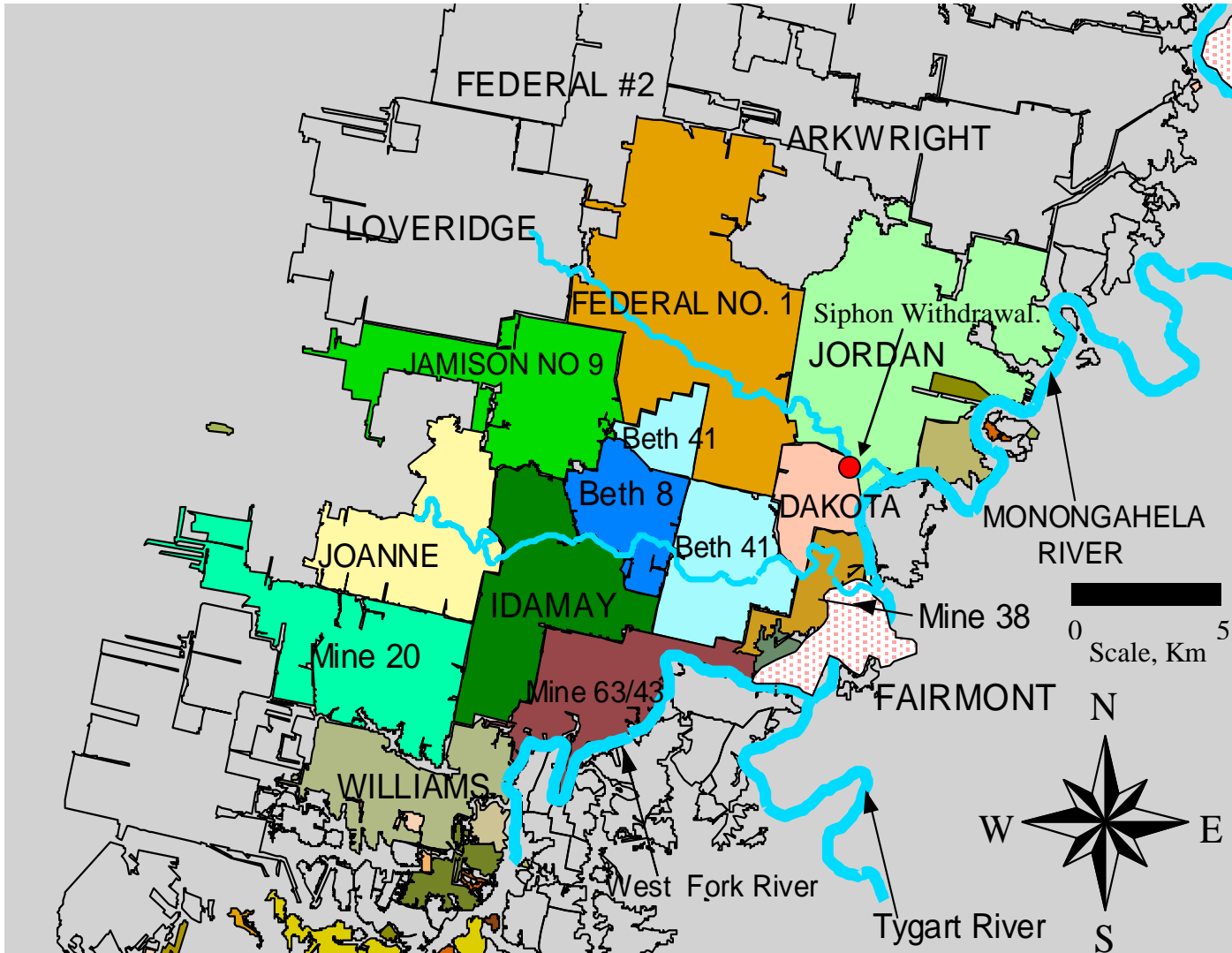


Figure 2. Principal and adjacent mines in the Fairmont mine-pool, and Siphon withdrawal.

hectares and across several drainage basins. Mines closed at various dates from the 1940's to the 1980's, and were developed mostly by room and pillar methods with retreat mining in some areas. Active underground operations are located further to the northwest and southwest under thicker overburden. Barrier pillars, ranging in thickness from about 9 to 60 meters, separate individual mines. In one location, Mine 38 (Fig. 2), mine maps show that a barrier pillar is breached, allowing unrestricted hydraulic connection between two mines.

An internal coal company report (Leavitt, 1993) predicted that potentiometric head in parts of the Fairmont mine-pool would increase to surface discharge elevation by the mid 1990's. In 1997, the mining company began withdrawing water from the Fairmont mine-pool at the Dakota mine (Fig. 2), to prevent a polluttional discharge to surface waters. Water is siphoned over a barrier pillar at estimated mean rate of about 5700 Liters/minute into the adjacent Jordan mine complex. From there, mine water is routed to a centralized lime treatment facility. OSM, on behalf of the state of West Virginia, began monitoring water levels in the Fairmont mine-pool in 1997 to determine if the Siphon withdrawal would maintain mine-pool head below discharge elevation. West Virginia University and a mining company also began measuring water levels, and monitoring continues to the present.

### **Methodology**

OSM began recording monthly water levels at six existing locations in the Fairmont mine-pool in 1997. In 1999, OSM drilled 4 additional monitoring wells to provide data from specific mines where no monitoring access had been available. Three more wells were drilled in 2002 to provide additional information in the western and southern parts of the mine-pool. All wells were drilled using air rotary methods, with a screened interval placed at mine elevation. Several boreholes were examined with a down-hole video camera to determine the degree of fracturing and collapse in the overburden and at mine level. Pressure transducers were installed in five OSM wells and programmed to record water level and temperature on an hourly basis. Wells without transducers continue to be read monthly. Weather data including hourly precipitation, air temperature, and barometric pressure were obtained for weather stations at Clarksburg and Morgantown, WV, each located within 15 to 20 kilometers of the project area. Daily summary

weather readings were also obtained for a station at Mannington, WV, located within the project area.

Water quality samples have been collected from selected mine-pool wells at semiannual to annual intervals, and more frequently at the Dakota mine Siphon. Wells were purged until stable readings were obtained for pH, temperature and specific conductance. Collected samples were analyzed for Alkalinity, dissolved Fe, Al, Mn, Ca, Mg, Na, K, SO<sub>4</sub>, Cl, As, Ba, Be, Cd, Co, Cr, Cu, Ni, Pb, Sb, Se, Zn. Specific conductance, pH, Eh, and temperature were measured at the pump discharge, and total acidity is calculated from dissolved metals and pH. Selected samples have also been analyzed for Fe(II) and S(-II). A simple presence/absence biological reactivity test for sulfate reducing bacteria has been run on selected wells.

Geochemical calculations were performed using PHREEQC (Parkhurst and Appelo, 1999) and statistical calculations were run in Statgraphics for Windows, version 4.1.

### **Mine Pool Flow**

The Fairmont mine-pool includes at least eight large individual mines that respond to recharge, discharge and other stresses in unison. From south to north (Fig. 2), they include Williams, Mine 63/43, Idamay, Beth 41, Beth 8, Mine 38, Dakota, and Federal 1. Potentiometric head in other mines to the north, west, and south is less than the Fairmont mine-pool. These other mines receive leakage or outflow from the Fairmont mine-pool. Potentiometric head is increasing, however, in the Joanne mine to west, and this mine may become part of the Fairmont mine-pool in the future.

Inferred ground-water flow directions are shown in Fig. 3, based on average head measurements compiled for the year 2002. The flow pattern is complex, and results from barrier pillars maintaining head differences between mines, and different mine closure dates and flooding records. The principal direction of ground-water flow within the pool is from south to north towards the Dakota Siphon. Much of the flow through the Fairmont mine-pool originates from the Williams and Idamay mines, and is apparently funneled through Mine 43/63 and Mine 38 (Fig. 3) adjacent to the West Fork and Monongahela rivers. The Beth 41/8 mines in the center of the mine-pool currently are ground-water sinks; that is, ground-water flows into them

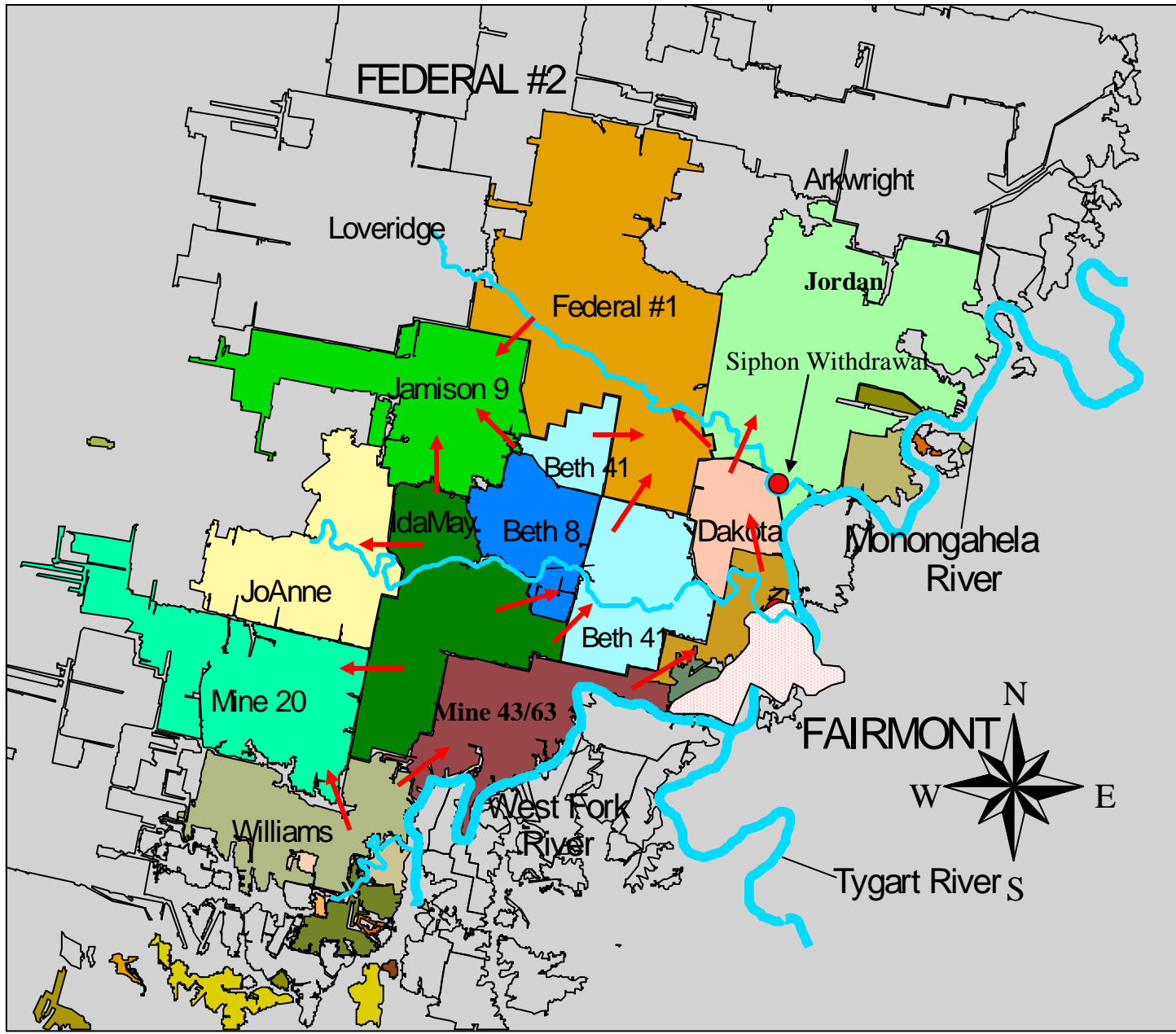


Figure 3 Generalized Ground-water Flow Pattern in the Fairmont mine-pool. Arrows indicate inferred flow direction based on head measurements and mine conditions.

from surrounding mines on the east, south and southwest. The Beth 41/8 mines do not contribute flow to the Siphon. However, potentiometric head is increasing and should equal or exceed the Siphon elevation within 3 to 5 years. At that time, the Beth 41/8 mines will cease to be a ground-water sink for the mine-pool. Instead, Beth 41/8 will contribute to ground-water flow to the Siphon.

Federal #1 mine constitutes the northwest part of the Fairmont mine pool. Its' potentiometric head is about six to eight m lower than the north end of Beth 41/8 which adjoins it, and about 10m less than the Dakota Siphon. Leakage from Beth 41/8 to Federal #1 is probably occurring. Federal #1 is a second major ground-water sink for the mine-pool. Both the Beth mines complex and Federal #1 have potentiometric head exceeding the Jamison 9 mine to the west, and are leaking into it.

Mine 20 and Jamison 9 to the southwest and northwest of the Fairmont mine-pool are pumped to protect nearby active mining. Large potentiometric head differences, on the order of 30m or more exist across the barrier pillars separating these mines from the Fairmont mine-pool. Leakage across the barrier pillars is another outflow for the mine-pool.

Mine-pool Response to Dakota Siphon Withdrawal

The Dakota Siphon began operating in April, 1997 and runs for about 10 months a year. Fig. 4 shows water levels at the Siphon; mine 38 located about 2.5 km distant, and the Williams

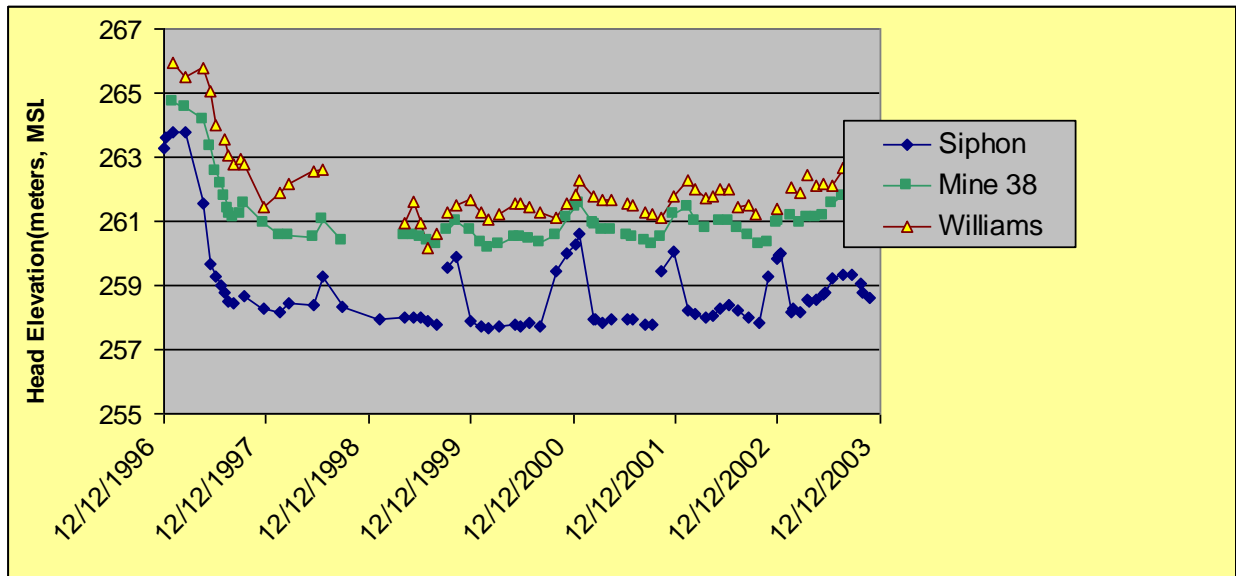


Figure 4. Water Levels at Dakota Siphon, Mine 38 and Williams Mine, 1997-2003.



mine well, which is about 18 km from the Siphon. The mine-pool was drawn down 4 to 5 meters once the Siphon began operating, even at the Williams mine at the opposite end of the mine-pool. The response is indicative of a confined aquifer. The drawdown is maintaining the mine-pool below the discharge elevation, and prevents a polluttional discharge to surface waters. Fig. 4 also shows that when the Siphon is shut off, potentiometric head begins to increase at the Siphon, and that recovery is mirrored at Mine 38 and Williams. After several months, when withdrawal resumes, the mine-pool is drawn down again. The Siphon will need to continue operation for the foreseeable term to maintain the mine-pool below discharge elevation.

#### Mine-pool Conductance Properties

A small hydraulic gradient exists within the mine Beth 41/8 complex, suggesting that individual mines have relatively high internal hydraulic conductivity. Water levels at three locations differ by less than two meters in wells separated by several km. Potentiometric head differences between mines are much larger, suggesting that flow is controlled mostly by barrier pillars. We have observed similar conditions of very low gradient between three wells in a single mine in Pennsylvania. Potentiometric head is less than 1 m difference among the three wells over approximately a 2 km separation. Simultaneously, there is a potentiometric head difference of 20 m across a barrier pillar to an adjacent mine (author's unpublished data).

We estimated barrier pillar leakage for one common boundary between the Beth 41/8 complex and Federal 1 mines (Fig. 3) from water level data, mine map information and horizontal hydraulic conductivity (K) data of McCoy (2002). He estimated effective hydraulic conductivity from pumping records and water level data for barrier pillars in two mines on the western side of the Fairmont mine-pool. McCoy reported a range of barrier pillar hydraulic conductivity of 0.03 to 0.15 m/day, and an average of 0.091 m/day. Using McCoy's average barrier pillar K, and an average head difference of about 7 m, we estimate that about 208 L/min flows through the barrier pillar between the Beth Mines complex to Federal 1, using a Darcy's law calculation. This is just one of a number of mine boundaries within the Fairmont mine-pool where flow across barrier pillars must be taking place. Management of the mine-pool requires consideration of total quantity of water circulating between mines via the barrier pillars.

Mine-pool Storage Properties

Ground-water storage in the Fairmont mine-pool includes water in the pore space of open mine voids and collapsed and fractured overburden, as well as an elastic storage component. Fig. 5 is a plot of hourly potentiometric head versus barometric pressure for a well in the Beth 41/8 complex during October, 2002. The two parameters are near mirror images of each other, a behavior that is characteristic of confined aquifers.

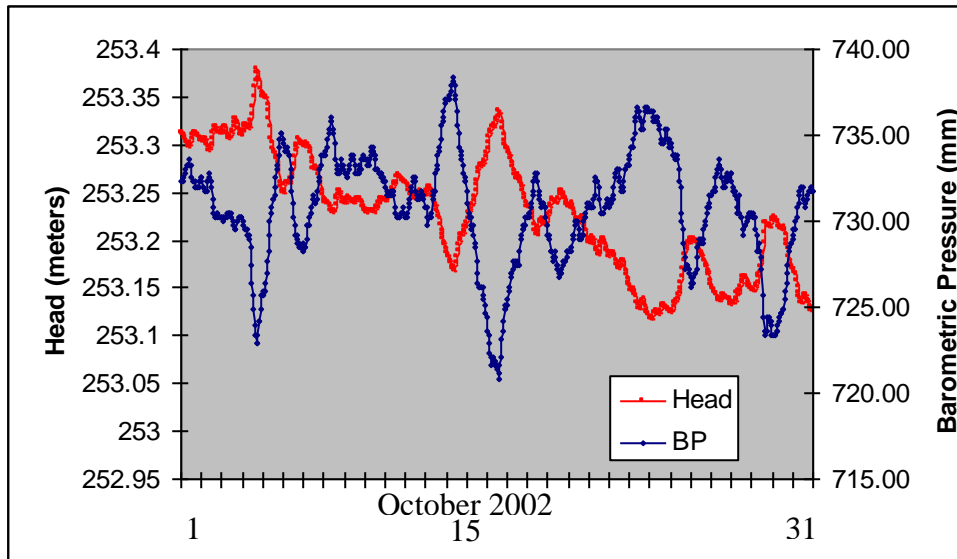


Figure 5. Hourly mine-pool potentiometric head versus barometric pressure, Beth41/8 mine complex, October, 2002.

The barometric efficiency (BE) of a well can be used to estimate specific storage,  $S_s$ , and porosity,  $n$ , of the aquifer (Domenico and Schwartz (1990) from the relationships:

$$BE = (y_w * dh) / dP_a \tag{1}$$

where  $y_w$  is the unit weight of water;  $dh$  is the head change; and  $dP_a$  is the change in atmospheric pressure.

$$TE = 1 - BE \tag{2}$$

$$TE = (p_w * g * B_p) / S_s \tag{3}$$

where  $p_w$  is fluid density,  $g$  is the gravitational acceleration constant; and  $B_p$  is compressibility of the aquifer matrix, either measured or estimated. Finally, porosity,  $n$  is estimated from:

$$BE = (p_w g n B_w) / S_s \quad (4)$$

where  $S_s$ ,  $p_w$ , and  $g$  are as previously defined, and  $B_w$  is fluid compressibility.

Portions of the record were selected where a change in barometric pressure persisted for at least 18 to 24 hours, such as occurred in mid October in Fig. 5. Underlying trends of rising or falling head due other factors such as seasonal variation were removed using regression methods similar to those described by Davis and Rasmussen (1993). Specific storage and porosity then were estimated using relationships 1 to 4. The process was applied to 3 to 5 different segments of the record to determine if reproducible results could be obtained. For individual wells, estimated values were generally within 25% relative difference.

Specific storage,  $S_s$ , was estimated to be about 1.5 to 2.5 x 10<sup>-6</sup>/m, and porosity estimates ranged from about 12 to 35% at three different wells. Most porosity values fell between 15 and 25%. These wells are completed in partially caved zones and crushed coal pillars, based on drilling observations. Since coal recovery typically ranged from at least 50 to upwards of 80%, these porosity data suggest the mine-pool aquifer thickness exceeds the coal thickness, perhaps by up to 6 times. On this basis, storage coefficient,  $S$ , for the aquifer, is estimated to be about 2x10<sup>-5</sup>. Crouch et al (1980), working, in a mine-pool aquifer in Ohio, derived a storage coefficient of about 3 x 10<sup>-4</sup> from a 29 day pump test after adjusting their hydrographs for barometric and seasonal effects. They concluded that pumped water was derived mostly from induced recharge and intercepted discharge. The apparent low storage coefficient for the Fairmont mine-pool results in relatively larger drawdown when it is pumped (siphoned).

### **Mine-Pool Water Quality**

Mine-pool water quality shows significant spatial variability. Table 1 includes analyses from wells located in a recharge area (Mine 38 well), intermediate flow-path (Mine 63) and end of flow-path for the mine-pool (Dakota Siphon). A fourth sample, Beth 42 overburden, is indicative of water quality in overlying aquifers that infiltrate and recharge the mine-pool. The mine-pool has circumneutral pH at each well, in each part of the flow system. Although the

initial charge of mine water in Pittsburgh seam mines is frequently acidic, complete flooding seems to curtail pyrite oxidation, and can bring about a shift of 3 to 5 S.U. in pH. Watzlaf (1992), in lab studies, found acid production was curtailed in saturated pyritic mine wastes, but continued in unsaturated materials. Donovan et al (1999) report a Pittsburgh seam mine-pool where pH shifted from about 4 to 6.5 after passage of about one pool volume. Winters (2000) describes a Pittsburgh seam mine-pool where acidic waters are present in the unsaturated up-dip end of the mine complex, shifting to circumneutral pH with alkalinity greater than 200 mg/L in the down-dip flooded end. Measured Eh values in Table 1 indicate moderate to strongly reducing conditions prevail, even in the recharge area at Mine 38. A reduced environment is consistent with inhibiting further pyrite oxidation once the mine-pool is fully flooded.

Table 1. Representative Water Quality of Fairmont Mine-pool<sup>(1)</sup>

Site	pH (field)	Alkalinity	TDS	Eh (mv)	Fe	Mn	Ca	Mg	Na	Cl	SO <sub>4</sub>
Mine 38	7.32	179.8	548	-94	3.44	0.53	60.7	14.1	105.7	34.1	207
Mine 63	7.31	589.6	3301	-130	33.9	0.64	158.4	33.1	853.4	44.2	1697
Dakota Siphon	7.20	568.7	5194	-159	134.8	1.63	250.6	89.7	1254	119.9	2812
Beth 41 Overburden	8.57	263	454	-146	0.04	0.016	21.0	5.0	138.3	52.1	47.9

(1) pH in S.U., Alkalinity in mg/L CaCO<sub>3</sub> Eq., Eh in mv, all others in mg/L. TDS= Total Dissolved Solids. Mine-pool samples collected 12/17/2002. Overburden sample collected 4/8/99.

There is about a tenfold increase in dissolved solids between recharge and discharge locations in Table 1, and about a threefold increase in alkalinity. During active mining, coal, roof and floor rock were exposed to humid oxidizing conditions, an ideal environment for pyrite oxidation, subsequent dissolution of other minerals, and formation of hydroxysulfates, oxides and other weathering products. Nuhfer (1967) reported finding hydroxysulfate minerals such as melanterite (FeSO<sub>4</sub>\* 7 H<sub>2</sub>O) and gypsum (CaSO<sub>4</sub>\*2 H<sub>2</sub>O) on exposed coal. Other metal sulfates including copiapite (Fe<sup>2+</sup>Fe<sup>3+</sup><sub>4</sub>(SO<sub>4</sub>)<sub>6</sub>(OH)<sub>2</sub>\*20H<sub>2</sub>O) and halotrichite (Fe<sup>2+</sup>Al<sub>2</sub>(SO<sub>4</sub>)<sub>4</sub>\*22H<sub>2</sub>O) (Jambor et.al., 2000) have also been identified in coal mines. These minerals are moderately

soluble, and can be expected to dissolve in the mine-pool, yielding dissolved Fe,  $\text{SO}_4^{2-}$ ,  $\text{Ca}^{2+}$  and other constituents.

Total alkalinities approach 600 mg/L in the intermediate flow path and discharge locations. These are among the highest values we have seen for nonsaline ground-waters circulating within 100 meters of the surface of upper Pennsylvanian rocks. The large alkalinity concentrations are likely due to a combination of carbonate dissolution and cation exchange. Limestones and calcareous rocks are abundant in the lower section of the Monongahela group (Hennen and Reger, 1913). The mine-pool aquifer consists not only of the residual coal, but also a zone of collapsed and severely fractured rock, which can range from 6x to 10x coal thickness (Kendorski, 1993). Rocks containing as little as 5 to 10 % carbonate are a large reservoir for generating solution alkalinity. Exchange of adsorbed Na for solution Ca and Mg would favor further dissolution of carbonates and production of alkalinity. Geochemical modeling has shown that carbonate dissolution and cation exchange are possible explanations for the observed changes in mine-pool composition (Perry, 2001). Sulfate reduction could also generate alkalinity. Sulfate reducing bacteria have been detected in the mine-pool along with trace levels of dissolved sulfide, ranging up to about 0.5 mg/L.

Rocks of the Monongahela group commonly contain illite, chlorite and kaolinite (Berryhill et al, 1971, Dulong et al, 2001), and clay mineral content of some mudstones and shales exceeds 20%. Cation exchange capacity (CEC) of kaolinite, and illite and chlorite ranges from about 3 to 15 meq/100g, and 10 to 40 meq/100g, respectively (Langmuir, 1997). For kaolinite, the lyotropic series for adsorption affinity is:  $\text{Na} < \text{H} < \text{K} < \text{Ca} = \text{Mg}$ . Exchange coefficients for Ca and Mg, with respect to Na, are about 0.40 and 0.50, following Gaines-Thompson convention (Appelo and Postma, 1993). Desorption of Na, and adsorption of Ca and Mg should be favored in these waters.

Even assuming very low CEC's of 2 to 5 meq/100g of rock, a large quantity of exchange sites are available in the aquifer along a flow path covering several to 10 or more km, and a residence time of years to decades.

Composition of mine waters also varies by location in the flow system. Recharge water at Mine 38 is a mixed Na-Ca- $\text{HCO}_3$ - $\text{SO}_4$  type; Mine 63 at an intermediate flow path position is a Na-  $\text{SO}_4$  - $\text{HCO}_3$  type water, while the Dakota Siphon at the end of flow path is a Na- $\text{SO}_4$  water. Mine-pool composition becomes progressively enriched in Na and  $\text{SO}_4$  as water moves from

recharge areas to point of discharge and there is an increase in dissolved solids concentrations. The changes are consistent with Na exchange and dissolution of sulfate minerals. The overburden aquifer is a Na-HCO<sub>3</sub> water, with much lower concentrations of metals and sulfate compared to the mine-pool. It is similar in composition to ground-water in Monongahela group rocks summarized by Hobba (1984) and Stoner et al (1987).

Table 2 shows mineral saturation indices for mine-pool waters calculated using PHREEQC (Parkhurst and Appelo, 1999). Recharge waters (Mine 38) are undersaturated for both calcite and dolomite, indicating carbonates should dissolve. Intermediate and end of flow path waters are slightly oversaturated for calcite and dolomite, suggesting that as water flows from recharge areas through the mine-pool, carbonates are dissolving. Mine waters are 3 to 5 orders undersaturated for melanterite, indicating that if present initially, it is dissolving. Gypsum is also undersaturated in recharge waters, but approaches equilibrium at the end of flow path. Amorphous or poorly crystalline Fe(OH)<sub>3</sub> is several orders of magnitude undersaturated, indicating that if present, it can dissolve. Goethite is, however; oversaturated for all waters, suggesting that some Fe could be removed from solution by formation of FeOOH. It has not been possible to collect sediments from the mine-pool for mineralogical analyses to verify the presence of specific minerals, however, the presence of each mineral in Table 2 is considered probable.

Table 2 Mineral Saturation Indices for mine-pool waters.<sup>(1)</sup>

Site	pCO <sub>2</sub>	Calcite	Dolomite	Gypsum	Goethite	Fe(OH) <sub>3</sub> (am)	Melanterite
Mine 38	-1.82	-0.52	-1.49	-1.40	2.29	-3.17	-5.09
Mine 63	-1.61	0.30	0.10	-0.54	2.93	-2.49	-3.68
Dakota Siphon	-1.54	0.27	0.28	-0.29	2.77	-2.70	-3.01

(1) Saturation Index calculated as log (Ion Activity Product/Equilibrium constant)

Iron is the chief pollutant of concern in the mine-pool because of deleterious effects on biota, aesthetics, and consumptive use at relatively low concentrations. Iron concentrations at the Dakota Siphon are about 40 times greater than the recharge area at Mine 38. Periodic sampling of these wells and others in the mine-pool has shown that Fe exhibits a high spatial variability, and that variation is maintained through time. Other parameters also vary spatially, but to a

lesser degree. Each well, however, tends to show a characteristic composition through time suggesting that a local equilibrium condition exists.

Fig. 6 and 7 show Fe and SO<sub>4</sub> concentrations; and a moving average based trend, for the six year period of 1997 to 2003. Both parameters, especially Fe, show scatter in raw data. Iron concentrations increased for about the first year of mine-pool withdrawal. Both parameters then began a gradual, somewhat irregular decline continuing to the present. Linear and exponential functions were fitted to the trend data for Fe and SO<sub>4</sub> from late 1998 to 2003, and to a smaller set of samples that had analysis for all major cations and anions. The exponential function is:

$$C_t = C_0 * \exp^{-kt} \quad (5)$$

where C<sub>t</sub> is concentration at time t, C<sub>0</sub> is concentration at time zero, k is a constant in time<sup>-1</sup> and t is elapsed time. The constant k, was estimated as the slope of a plot ln(C<sub>t</sub>/ C<sub>0</sub>) versus t. The linear and exponential models gave a range of estimates of the rate of concentration decline. The models were similar in their ability to describe the data, based on examination of correlation coefficients and residuals. The subset of complete suite samples had less variation and more clearly defined trends. Correlation coefficients for the subset were -0.81 for SO<sub>4</sub> and -0.73 for SO<sub>4</sub> for a linear model.

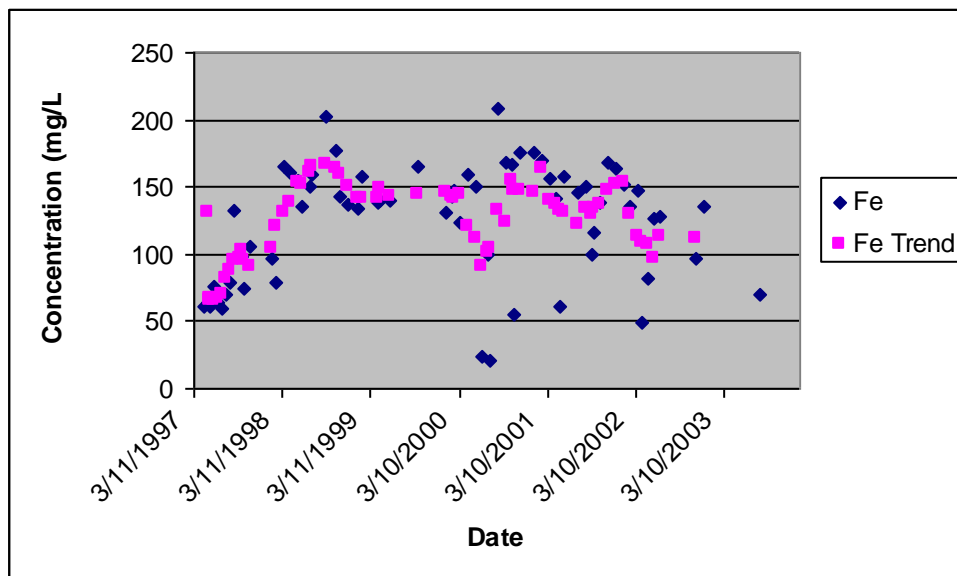


Figure 6. Raw and trend Fe concentrations, Dakota mine Siphon.

Time for concentrations to decline 50% is estimated at about 9 to 12 years for Fe, and 10 to 14 years for SO<sub>4</sub>, based on the regression models. For the period of record, SO<sub>4</sub> concentrations have declined from about 4,000 to 3,000 mg/L, and Fe from about 150 to around 100 mg/L. Mine-pool quality is improving, but slowly.

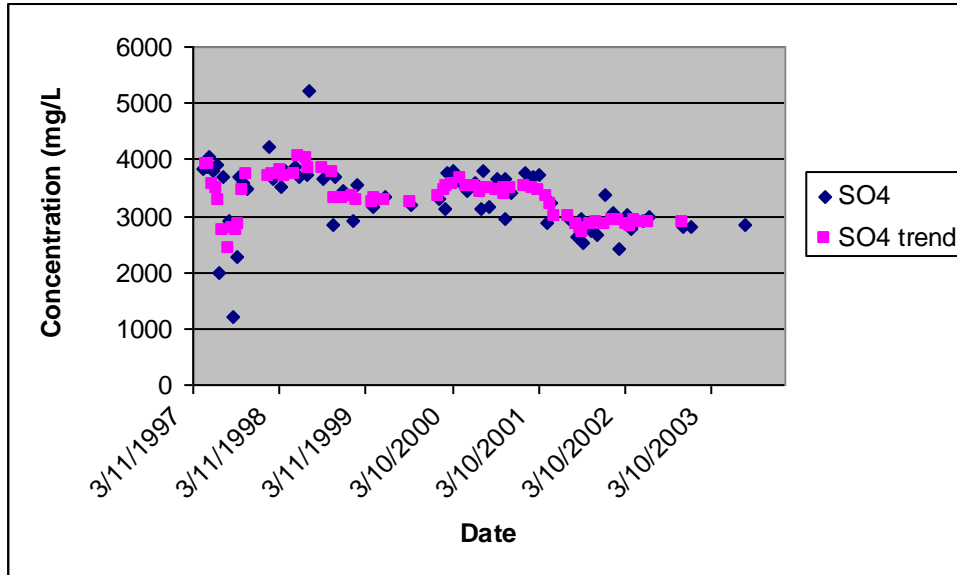


Figure 7. Raw and trend SO<sub>4</sub> concentrations, Dakota Siphon

Manganese concentrations follow a trend similar to that shown for Fe and SO<sub>4</sub>. Concentrations were 2 to 3 mg/L when the Dakota Siphon began operating, and have declined to about 1.5 mg/L at present. Time for concentration to decline 50% is estimated at about 8 to 9 years, based on a linear regression model.

Trace element concentrations are below detection limits for Be, Cd, Cu, Ni, Pb, and Sb. Small amounts of Ba and Zn are present at concentration of less than about 0.02 and 0.04 mg/L, respectively, and Co and Se have exceeded detection limits in some samples.

Initial Na concentrations were about 1400 mg/L at the Dakota Siphon, and are decreasing more slowly than Fe, SO<sub>4</sub> or Mn. Sodium still exceeds 1000 mg/L, and current behavior suggests that more than 20 years are needed for a 50% decline in Na concentration. Total dissolved solids (TDS) behavior is similar to Na.



### Conclusions

The Fairmont mine-pool is a group of hydraulically connected and fully flooded abandoned underground mines. The mine-pool responds to stresses, such as pumping, as a partly confined to confined aquifer. Individual mines have relatively high internal conductance, with small hydraulic gradients. Most potentiometric head differences occur across barrier pillars, and the location and orientation of barrier pillars, and flooding history result in complex flow patterns. Recharge to the mine-pool is offset by withdrawal from the Dakota Siphon, leakage to adjacent mines and outflow to unmined areas.

The Dakota Siphon has maintained the mine-pool below surface discharge elevation for over 6 years, and influences portions of the mine-pool located more than 15 km away. However the mine-pool has not yet reached a final steady state, as potentiometric head continues to increase in some mines in and adjacent to the mine-pool. The rate of withdrawal from the Siphon will likely need to be increased in the future to maintain the overall mine-pool below discharge elevation. Potentiometric head would increase to discharge elevation within a short period, if the Siphon withdrawal was stopped.

Mine-pool quality exhibits both spatial and temporal variation, especially for soluble Fe. Mineralization occurs least in inferred recharge areas, and increases as water moves through the ground-water flow system. Water composition evolves from mixed in recharge areas, to Na-SO<sub>4</sub> type waters at the end of flow path with high concentrations of alkalinity. The changes are consistent with dissolution of soluble sulfate minerals and cation exchange.

Complete flooding yields a reduced environment that seems to prevent further sulfide oxidation and favors sulfate reduction. The mine-pool is now undergoing a slow flushing of soluble weathering products. Discharge quality at the Siphon has shown some improvement through 6 years of monitoring, but remains unacceptable for consumptive or recreational uses without treatment. Dissolved solids, Na, Fe, and SO<sub>4</sub> concentrations remain problematic.

The Fairmont mine-pool will require continuing management for the foreseeable term to prevent a polluttional discharge.

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