Hydraulic sealing of an abandoned up-dip drift mine for AMD treatment: An 18-year post-audit

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Abstract

An abandoned underground coal mine in Vinton County, Ohio was sealed in 1979-1980 by a 1000-ft subsurface clay dike and mine-entry seals near the down-dip outcrop of the coal. The intent was to flood the up-dip drift mine to suppress oxidation of sulfide minerals and limit generation of acid mine drainage (AMD) that destroyed fish habitat in Lake Hope 3.5 miles downstream. Studies by USGS in the first three years after sealing showed continued acid seepage driven by high hydraulic head in the sealed mine, but an assessment of mine sealing could not be made because the hydrologic system had not stabilized. Water-level data collected 0, 4, 7 and 18 years after sealing show a pH increase from 2.7 to 5.3 in the mine and specific conductance decrease from 2700 to 600 µS/cm. Low dissolved oxygen (<2% saturation) is consistent with partial suppression of pyrite oxidation. Hydraulic head appears to vary seasonally with recharge. Mean concentrations of total acidity, iron, manganese, and aluminum decreased 49% (47 to 24 mg/l), 85%, 19% and 69% respectively, in Big Four Hollow adjacent to the sealed mine. Except for pH which is log-distributed, variability of all parameters as measured by standard deviation decreased 14--96% between 1979 and 1997. Concentrations are highest at low flow. The loading (concentration × flow) of acid and metals is lowest at low flow. Mean loading of acidity decreased 75% since 1979. Iron, manganese, and aluminum loading decreased 90%, 66% and 85% respectively. The sealed mine shows decreases of as much as 64% of the predicted 18 mg/l acidity decrease in Sandy Run, but some amount may be due to natural attenuation. An adjacent unsealed mine also shows substantial improvement: Mean concentrations of total acidity and iron decreased 9% and 71% respectively, but concentrations of manganese and aluminum *increased* 13% and 11% respectively, in upper Sandy Run adjacent to the unsealed mine. Mean loading of acidity from the unsealed mine decreased 46%. Improvement in the unsealed mine is attributed to natural attenuation or to annual variability., because the two mines are hydraulically disconnected. Some natural attenuation is expected in both mines due to strong and extensive sandstone roofs with absent shale, which prevents mine collapse, thereby limiting the fresh surfaces exposed to oxidation. The sealed mine fell short of projected improvement because year-around inundation of the mine works has not been achieved. The water level in the mine rises during recharge periods, and declines through the summer due to leakage through natural geologic materials or the seal itself.

Introduction

Damming Sandy Run formed Lake Hope in 1939. Below 120-acre Lake Hope, Sandy Run empties into

Raccoon Creek, tributary to the Ohio River. Lake Hope lies in a 10 mi^2 watershed in Vinton County, Ohio, and receives acid mine drainage (AMD) from underground coal mine complexes 88 and 47, located under adjacent ridges . In the mid-1900's, acid discharge into adjacent streams and Lake Hope caused fish kills. In 1980, after several efforts to treat AMD, Complex 88 was sealed with 35 mine-entrance hydraulic seals and a 1000-ft subsurface clay dike along the down-dip coal outcrop (**Figure 1**).

Comparison of the water quality before and after sealing (Nichols, 1985; Nichols, 1983) showed no apparent improvement in stream quality (Biaglow, 1988). More recently, fish density and size were found to be average or better than similar populations statewide (Greenlee, 1998), prompting an 18-year re-assessment of the mine sealing. This study tested the hypothesis that loading of acidity from the sealed mine became more uniform due to mine water storage and slow release, eliminating "slugs" of acid.

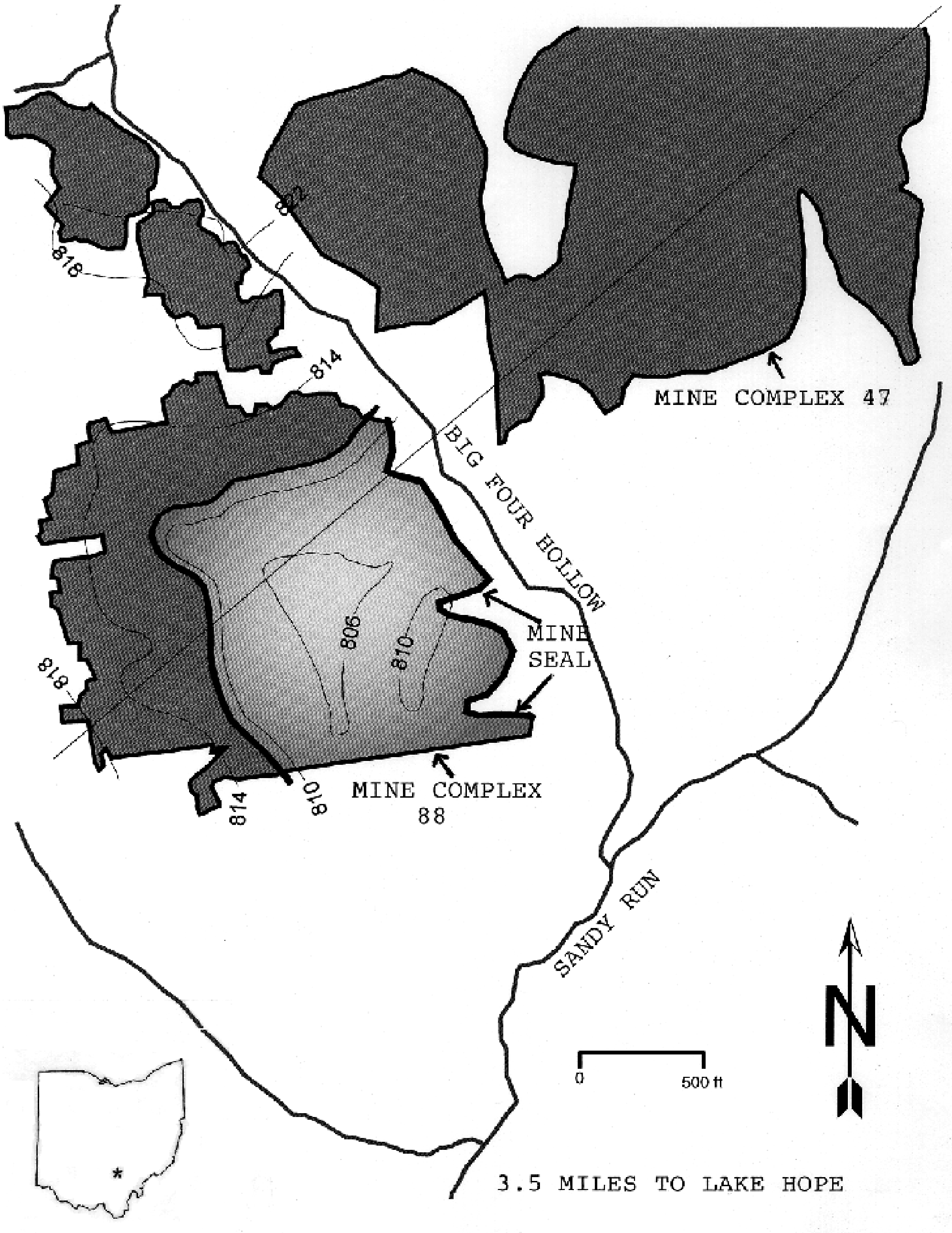

Figure 1. Generalized map of Mine Complexes 88 and 47. Light variably shaded area is flooded by hydraulic sealing of mine entrances and a clay dike along the coal outcrop, indicated by the heavy line on the east side of Mine Complex 88. Mine floor contours are in feet.

To test this hypothesis, water level and several chemical parameters were logged in the mine pool, and water quality and flow were measured monthly in Big Four Hollow, the stream draining the sealed Mine Complex 88. Similar monthly measurements were made in upper Sandy Run, which drains nearby unsealed Mine Complex 47.

The rate-limiting reaction in the production of AMD is the oxidation of pyrite, in which ferrous iron is converted to ferric iron in the presence of oxygen and catalyzing microbes (Nordstrom and Southam, 1997). Many strategies have been used to limit the release of AMD from mines and mine spoils, with varying success, including alkaline amendments, bactericides, dry barriers to water and air, and flooding to suppress oxidation (Skousen and Ziemkiewicz, 1995). Lab column studies found pyrite oxidation rates to be independent of oxygen partial pressures down to 1% (Hammack and Watzlaf, 1990).

Water is the only barrier capable of economically maintaining such low oxygen levels, so the best way to limit pyrite oxidation is to place pyritic material below a permanent water table (Hammack and Watzlaf, 1990): In experiments with inundation, a 96% reduction in pyrite oxidation was achieved. Subaqueous disposal of sulfidic tailings in lakes is widely favored (Fraser and Robertson, 1994; Amyot and Vézina, 1997).

Sealing of underground mines for AMD control was researched as early as the 1920's by the U.S. Bureau of Mines, following observations that mines sealed by cave-ins discharged less acidic water than others (Foreman, 1971). The Works Progress Administration (WPA) in 1933 started a $5.4 million sealing program that at least temporarily reduced by 28% acid loading to the Ohio River. Failures of WPA seals, caused reluctance among miners to continue sealing (Foreman, 1971).

The change in water quality following inundation can be dramatic, especially in sub-drainage mines, which have been reported to become net alkaline within 10 years, with up to 500 mg/l alkalinity but with 50 to 200 mg/l ferrous iron (Ziemkiewicz, 1998). In a study of 65 mines closed by all known methods, closures reduced acidity (Bucek and Emel, 1977). Flooded shaft/slope and drift mines showed better quality than discharges from open, air- or dry-sealed, or partially flooded up-dip drift mines. The closures also reduced variability of water quality. The physical and mining framework of the sites was a better predictor of water-quality improvement than closure method. Flooded mines in Wyoming showed marked improvement since inundation between 1968 and 1980 (Ladwig, 1985). pH increased to near neutral at all of the outfalls and net acidity decreased. Short-term performance of seals installed in the 1960's showed 40-100% reduction in acidity, with 80% to be expected with a good seal design and proper installation (Foreman, 1971). A flooded lead-zinc mine showed a pH increase from 3 to 6 in seven years (Neukirchner and Hinrichs, 1997). In a flooded metal mine pH increased from 2 to 4 in three years and zinc and copper loads decreased 90-95% (Arnesen and Iversen, 1997). A drift mine seal at Moraine State Park, similar to the mines near Lake Hope, resulted in a 75% reduction of acidity (Harris, 1973).

Hydrology and geology

The Allegheny Formation of the Pennsylvanian System outcrops near Lake Hope (Stout, 1927; Marple, 1954), with strata striking N20°E and gently dip 0.3°SE. The Middle Kittanning No. 6 Coal, the primary seam in the area, has a 1.1 to 3% sulfur content (Sedam, 1991). The coal is a uniform 4 ft thick, based on 16 test holes. The coal was mined up-dip, facilitating gravity drainage. Massive sandstone lies directly over the coal with no intervening shale. The sandstone thickness, where the entire section is present, ranges from 14 to 44.5 ft, constituting 67 to 90% of the overburden. Where sandstone is the topmost rock unit, its thickness ranges from 7 to 31 ft, constituting 100% of the consolidated overburden. Thin clay or shale layers interrupt the sandstone in two of the test holes, but in these two cases at least 24 ft of uninterrupted sandstone directly overlies the coal. The kaolinitic underclay ranges from 3.5 to >7 ft. Drilling terminated in clay in 9 of 16 test holes, so clay thickness is unknown. The underclay supports overlying formations without deformation (Stout, 1927), but may be unstable when saturated (Stanley Consultants, 1973).

Water enters the mine by seepage through the Lower Freeport Sandstone and through secondary porosity within this sandstone formed by jointing (Biaglow, 1988). Upon reaching the coal seam, water flows freely through horizontal voids in the coal. A survey conducted in 1973 revealed 107 abandoned mine entrances associated with these two complexes (Harris, 1973), with an estimated combined acid loading of 2000 lb/day based on limited data. Mine Complex 88 drains into Big Four Hollow down-dip from that complex, to the east. Mine Complex 47 drains into Sandy Run, also down-dip from the complex to the east. Big Four Hollow joins Sandy Run just downstream from the mines, and the combined AMD from both mines degrades water quality in Sandy Run and Lake Hope. A geological investigation of the mines in the watershed challenged proposed mine sealing by suggesting that the rocks of the mine walls and underclay in the mine floors are unstable and would leak under the high hydrostatic pressures that develop after sealing, precluding inundation (Harris, 1973). Ohio Department of Natural Resources (ODNR) and the Ohio Environmental Protection Agency (OEPA) completed construction of the seal using a design by Gwin, Dobson and Foreman (Foreman et al., 1979), which included a clay dike to counter possible seepage through the coal outcrop where workings extended into shallow cover (Foreman, 1971) (**Figure 2**). A 1000-ft trench was excavated and blasted parallel to the coal outcrop, exposed mine tunnels were plugged with expansive cement, and then the trench was filled with clay and a support backfill. In addition, 35 mine entries were hydraulically sealed with clay supported by concrete walls (Nichols, 1985).

Data collected by USGS during the first six months after construction indicated moderate improvement in water quality, and large decreases in sulfate and iron loading (Nichols, 1985). A conclusive statement about the mine sealing could not be made at that time because the mine was still filling and not yet flushing out excess water (Nichols, 1983). Two years later, increased hydraulic head behind the clay dike caused the mine water to leak and degrade the stream-water quality. A definitive evaluation of the seal could not be made because the hydrologic system had yet to stabilize. A subsequent study concluded that little to no improvement in water quality had occurred in the short-term post-sealing period, and in fact, some parameters showed deterioration (Biaglow, 1988). Although a temporary increase in acidity due to construction disturbance was anticipated (Stanley Consultants, 1969), the 1987 study concluded that water quality might have been better without the seals, allowing natural attenuation to take its course (Biaglow, 1988). Recent obvious improvements in Lake Hope challenge that conclusion.

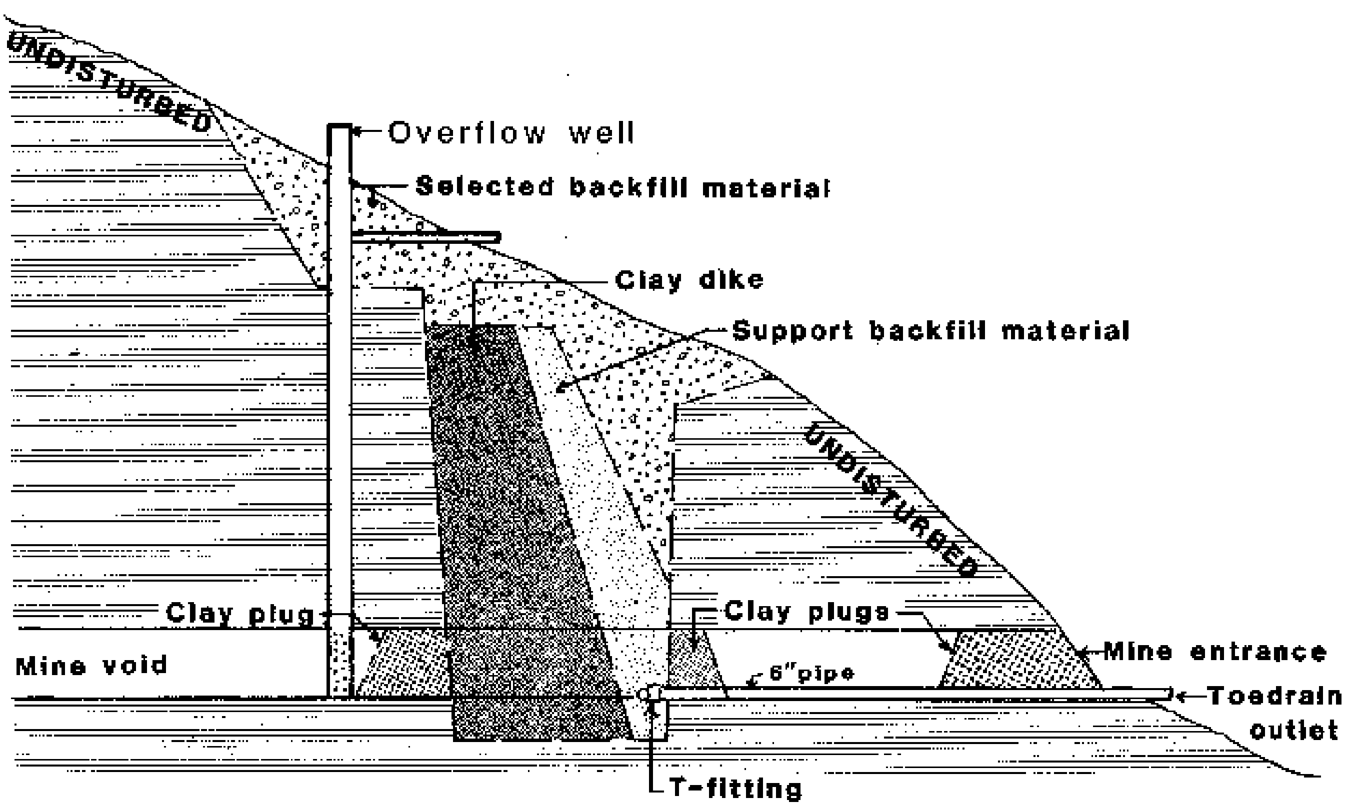

Figure 2. Schematic of the mine seal and clay dike (Nichols, 1985).

Methods

Three samples were collected monthly at Sites 1 and 3, including a 1-liter grab sample, a 250-ml unfiltered sample preserved with 5 ml of 30% HNO_3 for total metal analysis, and a 250-ml sample filtered with 0.45 mm syringe filters and preserved as above, for dissolved cation analysis. Specific conductance, pH, TDS and temperature were measured in the field with a Corning CheckMate. Samples were analyzed at Coshocton Environmental Testing in Coshocton, Ohio. Concentrations are reported as dissolved species where such data are available, and otherwise are reported as total species. In the case of loading calculations, total metals are reported. Acidity was measured by the hot peroxide method. Discharge in Big Four Hollow and upper Sandy Run was measured approximately monthly using a top-set wading rod and pygmy current meter or bucket and stopwatch. Stream flow reported for 1978-1983 was measured at surface-water stage-discharge stations using USGS methods (Nichols, 1985).

The mine pool was sampled at USGS observation well RM-1 (Nichols, 1985) from June 1997 to January 1998 (Wanner, 1998). Mine water level, temperature, pH and specific conductance was recorded every four to twelve hours with a Campbell Scientific CR10 datalogger.

Results

Discharge. Three small streams and one hillside seep exit Mine Complex 88. In addition, diffuse AMD occurs through pores and fractures and appears as iron hydroxide in the stream or as wet areas either with *Sphagnum* moss or iron hydroxides. Several up-dip points discharged AMD in the March 1997 storm. No base-flow discharge of AMD was apparent downstream. Unsealed Mine Complex 47 discharges freely from several mine entries which coalesce and flow into upper Sandy Run. Groundwater in the underlying sandstone aquifer was tested in 1981 by sampling an abandoned well drilled down-gradient of mine entrance 90 (Nichols, 1985). The land surface at the well is about 20 ft below the mine floor, and the well is 31 ft deep. The groundwater had a pH of 8.2 in July 1981, indicating that mine water had not penetrated the underlying sandstone aquifer within a year of sealing. Present extent of contamination, if any, of the underlying sandstone is not known. Mine Complex 88 discharges acidic water as small streams and seeps throughout the year, but especially during seasonal periods of heavy rainfall, when hydrostatic pressure builds in the mine. Increased seepage presumably is driven by higher pressures (Aljoe, 1994). Leakage may occur through bedding-plane fractures that develop parallel to the mine floor due to release of rock pressure during mining (Foreman, 1971; Wyrick and Borchers, 1981), and through the peripheral coal barrier. The potential for water to migrate around the mine seal area and through peripheral barriers was anticipated and was in part compensated for in the seal design, in this case through installation of a clay dike, and in other cases through grouting (Foreman, 1998; Foreman, 1971). Leakage can lead to dissolution and piping of the rock surrounding the seal, and high water levels in the mine may deteriorate the mine roof, especially in areas where it consists of shale (Moebs and Sames, 1989). Abrupt seal failure due to hydrostatic pressure is less of a concern than long-term loss of the ability of the seal to hold water due to piping or erosion of the rock: seals usually can withstand much greater hydrostatic pressures than those imposed on the seal in Mine Complex 88. For example, inundation bulkheads in deep mines may experience pressures up to 1000 ft of head (Chekan, 1985). The Mine Complex 88 seal, in contrast, can experience pressures only up to 17 ft before pressure bleeds off at an up-dip overflow.

Changes in the mine pool. Hydraulic head, specific conductance, pH, dissolved oxygen and temperature support the conclusion that mine sealing has suppressed AMD generation. Heads increased after construction ended in April 1980, rising to a level below full inundation (**Figure 3**). Head varies seasonally with recharge, showing summer declines. AMD has been decreasing since sealing even though full inundation was not achieved. Specific conductance has decreased from 1979 to 1997, and pH has increased (**Figure 4**).

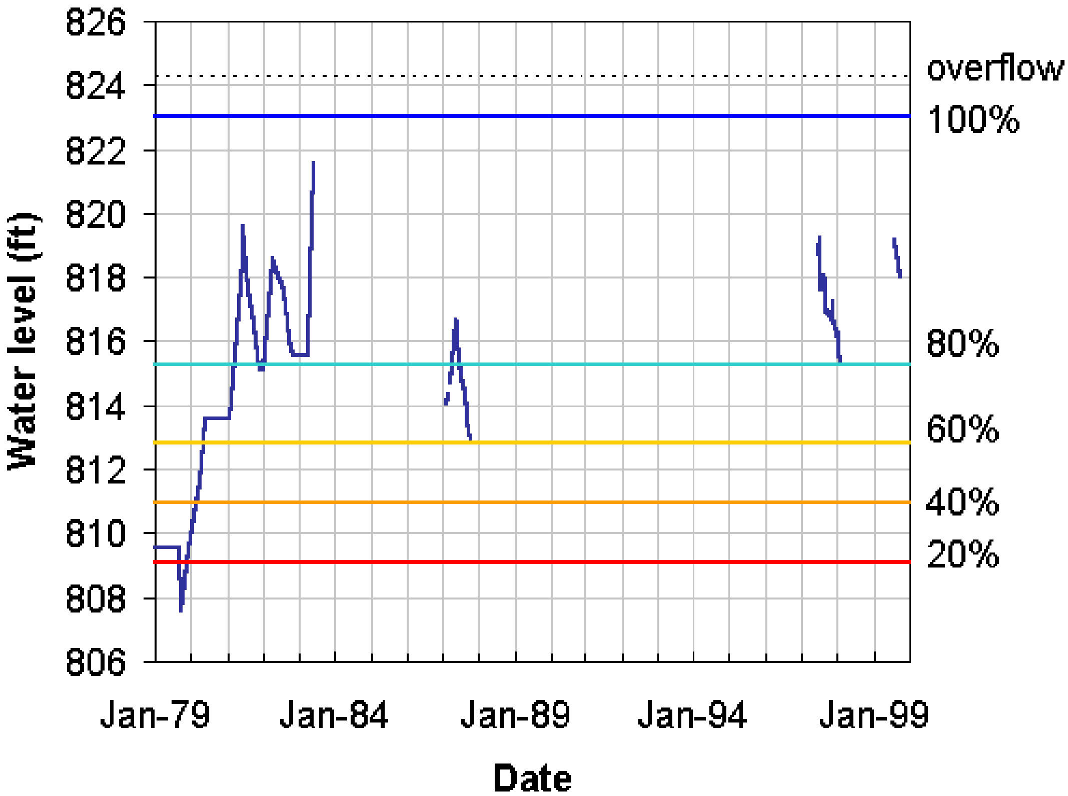

Figure 3. Water levels measured in the sealed mine, 1979 to 1999. Corresponding percent inundation is shown on right axis. Data from Nichols (1985), Biaglow (1988), and Wanner (1998).

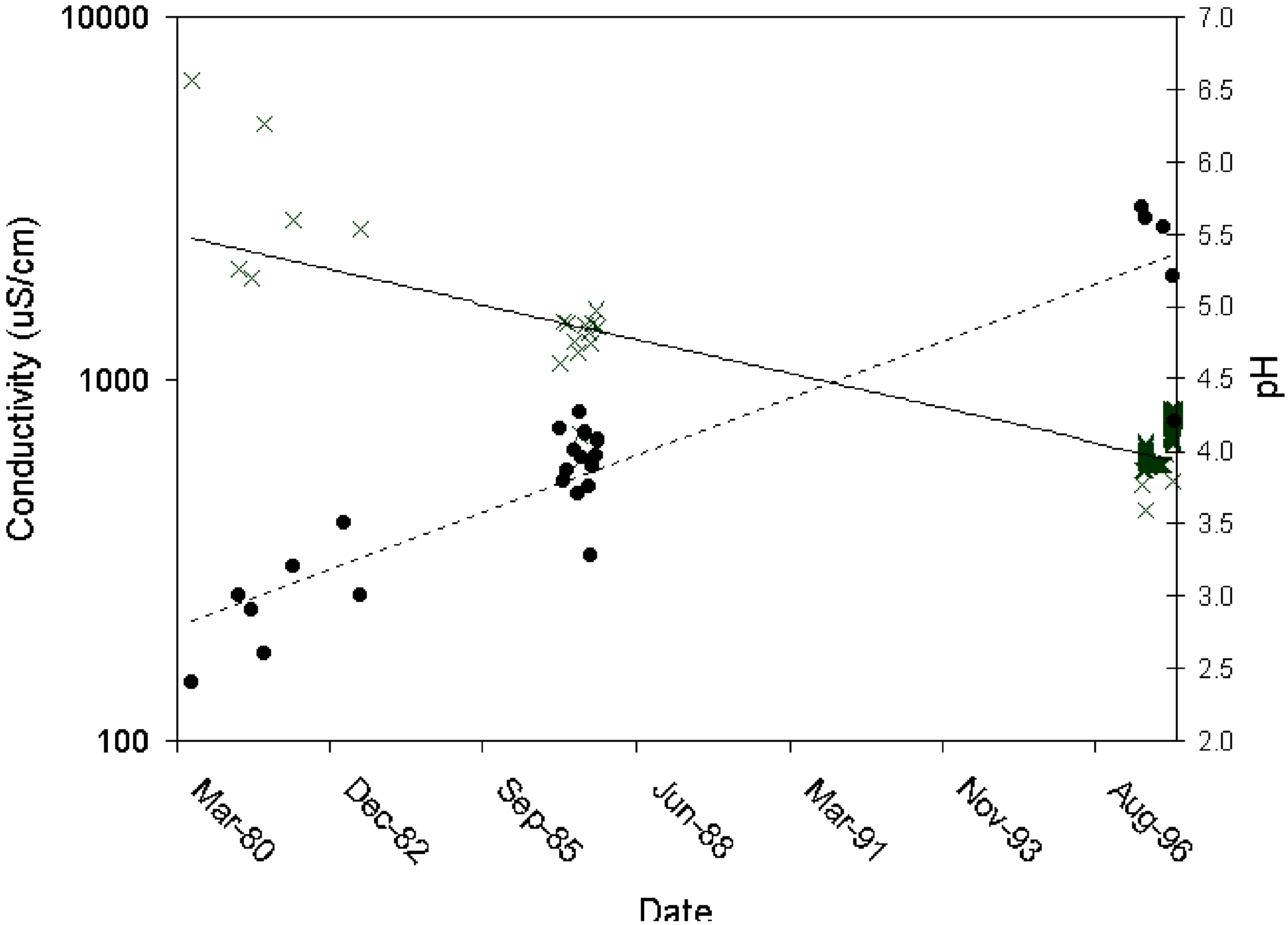

Figure 4. Variation in pH (circles) and specific conductance (x's) in the sealed mine from 1979 to 1998 (Nichols, 1985; Wanner, 1998; Biaglow, 1988).

Arguably, dilution by infiltrating rainwater could have raised pH and lowered conductivity, but in other mine complexes in southeast Ohio (Pigati, 1997; Stachler, 1997) solubility rather than dilution controls water chemistry. Decreasing specific conductance and iron (not shown) suggest that mineral acidity is not increasing. Dissolved oxygen (DO) measured during a single sampling of well RM-1 was 2% or less at depths below 8 ft (Wanner, 1998).

Water quality and chemical loading. Stream discharge at Site 1 and Site 3 ranges from near 0 to almost 60 l/s (2 cfs) (**Figure 5**).

Stream flow responds to precipitation more in the winter and spring than in the summer and fall, probably because more infiltration occurs in the summer and a soil moisture deficit persists into the fall. As a consequence, discharge was high January to June and low July to December. Volumetrically, the mine flows are a small percentage of stream discharge, so a comparison of hydrographs between the two sites does not show striking differences. However, hydrographs from water year 1981 show that the sealed mine sustained a somewhat higher flow in the summer months than the unsealed mine, a pattern not evident before sealing (Nichols, 1985). Field inspection of the two mine discharges confirms that the sealed mine continues to flow even during dry weather, whereas the unsealed mine responds quickly to precipitation or reflects the lack of it. The logical explanation is storage and slow release of water in the sealed mine.

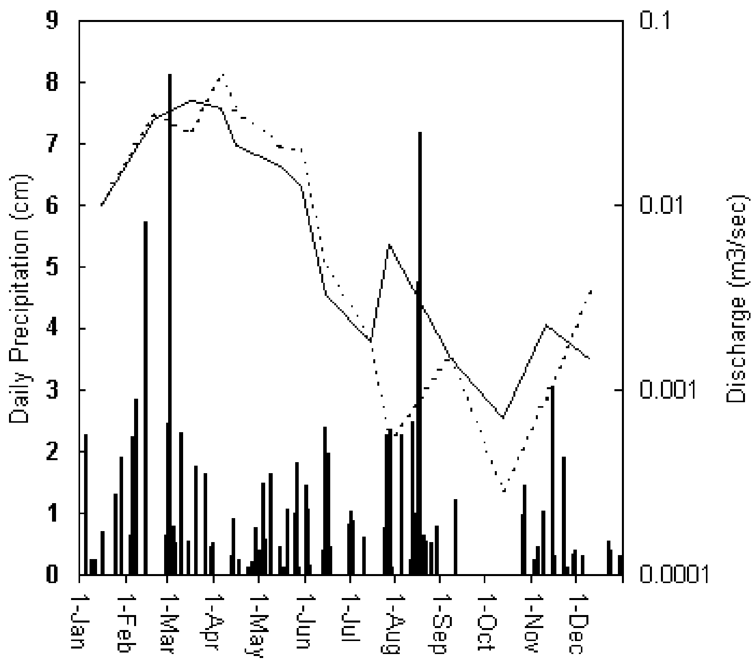

Figure 5. Stream discharge at Sites 1 (solid lines) and 3 (dashes). Bars are precipitation.

The mean stream pH has increased 0.5 units at Site 1 and 0.1 units at Site 3 from 1979 to 1997 (**Figure 6, Table 1**). Increases were greatest at high flow in the late winter and spring; summer and fall pH's were close to or worse than 1979 conditions. pH is positively correlated with flow, with the highest pH measured at high flow when AMD is diluted by stream water. Under low streamflow conditions, leakage of stored mine water lowers pH to near 4 at low flow. The unsealed mine discharges more water at high flow than the sealed mine, so dilution by stream water does not cause as great a decrease in H^+ concentration at Site 3, and pH remains below 4.6. As a general rule, pH increases as streamflow increases at both sites, but the effect of streamflow dilution is greater at Site 1 because the mine stores acid during high flow.

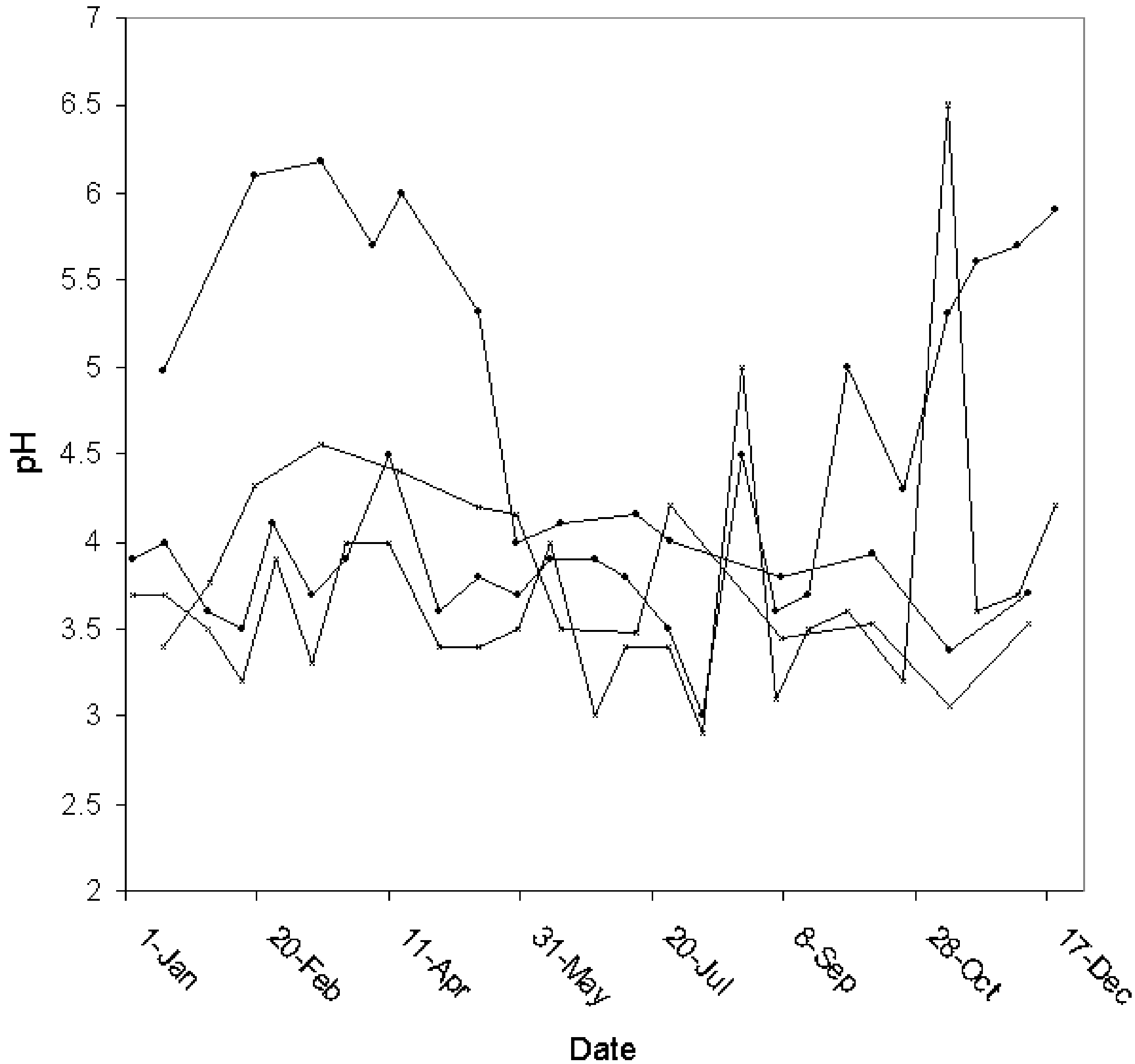

Figure 6. Annual variation in pH at Sites 1 (circles) and 3 (x's), for 1979 (light lines) and 1997 (heavy lines).

	1979 Mean	1997 Mean	Change
Site 1			
pH	4.2	4.7	**12%**
Specific Conductance	457	419	**-8%**
Acidity	47	24	**-49%**
Total Iron	9.2	1.4	**-85%**
Total Manganese	2.1	1.7	**-19%**
Total Aluminum	3.2	1	**-69%**
Site 3			
pH	3.7	3.8	**3%**
Specific Conductance	633	673	**6%**
Acidity	81	74	**-9%**
Total Iron	11.9	3.4	**-71%**
Total Manganese	1.5	1.7	**13%**
Total Aluminum	5.5	6.1	**11%**

Table 1. Mean monthly water quality at Sites 1 and 3, 1979 and 1997. Units (except pH) are mg/L.

Acidity at Site 1 has decreased since 1979, in both magnitude and variability. Low acidity values were recorded at Site 3 in summer of 1979 and at both sites in fall of 1979 when dilution by surface runoff resulted in net alkaline flows. Mean acidity has decreased from 47 to 24 mg/l at Site 1, and 81 to 74 mg/l at Site 3. A reduction of 18 mg/l in Sandy Run was projected to follow sealing of Mine Complex 88 (Harris, 1973). Since Site 3 flow is 50% of flow in Sandy Run just below Big Four Hollow, this is equivalent to a projected 36 mg/l decrease in Big Four Hollow. The actual decrease is 23 mg/l. The mean annual acidity reduction at Site 1 is 49% and at Site 3 is 9%. Standard deviations of acidity values have decreased 73% at Site 1 but only 10% at Site 3. Relative uniformity of the water is expected as a consequence of sealing because the mine pool slowly releases stored water. Because 1987 water quality did not show marked improvement over 1979 water quality, before 1997 sampling it was hypothesized that damping of concentrated peaks of acidity and metals was responsible for improvement in Lake Hope fish populations (Ahmad, 1970). At that time, the pH of Lake Hope was normally 4 to 5 resulting in a meager fish population. Elimination of acid slugging and improvement in average water quality may both account for improvements in the fish population. Lake Hope near where Sandy Run enters now has a pH of 6.5 and net alkalinity.

Other parameters measured in Big Four Hollow follow the same general pattern, showing decreases in concentration and decrease of parameter variability. Mean specific conductance at Site 1 has decreased slightly (8%), while Site 3 shows increases. Specific conductance is overwhelmingly due to sulfate, which is conservative and does not reflect the overall metal or H+ concentrations. Specific conductance is an excellent indicator of the historic occurrence of mining but does not show effects of reclamation well. Because of low fall 1997 flows, specific conductance is higher in fall 1997 than in fall 1979. Iron concentrations have decreased at both sites (85% and 71% respectively) because redox potential and pH have increased such that dissolved ferrous and ferric iron are not stable, and iron precipitates. Iron concentrations drop sharply above pH 3.5. Iron is expected to precipitate at a pH near 3 for open and fully oxygenated systems (Whittemore and Langmuir, 1975), so the presence of dissolved iron at pH 3.5-4 may reflect reaction kinetics or incomplete mixing. Mean manganese concentrations show a 19% decrease at Site 1 and a 13% increase at Site 3, but are relatively unchanged, because manganese tends to remain in solution until the solution is quite alkaline. Manganese may co-precipitate with iron at near-neutral pH provided the iron/manganese ratio is very high, 30 or greater. Otherwise, manganese has been seen to precipitate at pH 8.8 to 10.5 (Hilton and Norman, 1998). As with specific conductance and iron, manganese concentrations are high in the fall when stream flow is low and dilution is less effective. Mean aluminum concentrations have decreased 69% at Site 1, but increased 11% at Site 3, again a consequence of the higher pH at Site 1. Aluminum precipitates around pH 4.6 as expected (Nordstrom and Ball, 1986). The pH at Site 1 is above this threshold except for low-flow conditions. As with the other metals, concentrations rise in the fall when the stream flow is low. Because aluminum is particularly toxic to fish, interfering with the gill function (Brocksen et al., 1992), treatment of AMD must raise the pH to at least 5 to prevent fish kills and loss of habitat. As a practical matter, certain species face losses as pH drops below 6 (Schofield and Driscoll, 1987) so pH 5 should not be used as a goal.

Acidity loading is the product of acidity and flow, expressed in lb/day. While acidity is important for stream conditions, acidity loading is a more important treatment design parameter and also influences the health of downstream areas, including Lake Hope. Acidity loading from Site 1 decreased from an average of 179 lb/day in 1979 to 45 lb/day in 1997, while the loading at Site 3 decreased from 215 lb/day to 116 lb/day. The decrease in acidity loading from the sealed mine is 75% and the decrease in loading from the unsealed mine is 46%. Comparing 1997 acidity to acidity loading, there is an inverse relationship. During low flow periods when the water is concentrated, the acidity loading is low because the stream discharge is low. In treatment design, the loading determines the buffering requirement, in 1997 reaching 300 lb/day $CaCO_3$ at Site 3 and 200 lb/day at Site 1. The total annual loading in 1997 at Site 1 was 8 tons and at Site 3 was 21 tons. In 1979, Site 1 annual acidity loading was 33 tons and Site 3 annual loading was 39 tons.

Conclusions

Water quality has improved, and metal and acidity loading have decreased, between 1979 and 1997. Because the comparison between the two years is so dependent on flow, the quantitative improvement should be interpreted cautiously.

Improvement in water quality may be in part due to natural attenuation. Water quality improved in the stream adjacent to unsealed Mine Complex 47 (Site 3), but the improvement was less than for Site 1.

The worst water quality is observed when the stream discharge is low, but the greatest treatment demand, in terms of buffering, is at high discharge. Concentrations of H^+, TDS and metals are strongly but inversely flow dependent due to dilution by high discharge. Loading increases proportionally with flow, showing more variability in the unsealed Mine Complex 47 because of variable flow.

Water quality in the mine supports removal of oxygen through flooding as a mechanism for lessening the production of AMD. The mine water itself is of uniform quality, and based on limited data appears to have improved gradually since sealing. A single dissolved oxygen profile showed levels below 8 ft depth to be less than 2% saturation.

Mine 88 leaks water, so complete inundation rarely is achieved. Nevertheless, 64% of the projected 18 mg/l acidity decrease in Sandy Run was achieved in 1997. The unexpected improvement of 7 mg/l from natural attenuation at Site 3 provided another 3.5 mg/l improvement in Sandy Run, for a net improvement of 15 mg/l.

The sealed mine acts as a leaky reservoir, slowly releasing water through three discrete seeps and by diffuse flow through pores in the surrounding rock. Recharge to this reservoir occurs during periods of high rainfall and low evaporation, usually in the spring. During periods of low rainfall or high evaporation, the water level in the mine declines.

Mine sealing has decreased the variability of water-quality parameters and flow. Storage and slow release of excess water in the mine pool results in a more even flow to the stream. Lake Hope does not receive the fish-killing slugs of acid seen in the past. In 1997, Site 3 water was more variable from month to month than Site 1 water, for all parameters. Because the mine reservoir continues to release water when the stream flow is low, concentrations of metals and acidity are highest at low flow. However, loading is lowest and at low flow so the high concentrations do not create the greatest stresses to the lake.

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