HYDROLOGIC INVESTIGATION AND REMEDIATION OF A POST-REMINING ACIDIC SEEP[1]

by

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Abstract. Surface remining of coal pillars in abandoned underground workings in the Pittsburgh seam in southwestern Pennsylvania has often resulted in post-remining discharges whose water quality is the same or better than the pre-existing discharges. However, at one such operation in Washington County, PA, an increase in contaminant loading occurred at an outcrop seep after remining. This problem was believed to be at least partly related to a small unstripped area of the old deep mine workings immediately upgradient from the seep. A hydrologic investigation that included a chemical tracer test, slug tests in the remined spoil, and water quality monitoring indicated that the mine pool in the old workings discharged through the seep. However, the water in the mine pool and much of the remined spoil was consistently alkaline; this suggested that the acidic water may have originated in other areas of the spoil and old workings, and passed rapidly to the seep through a highly transmissive portion of the spoil. Acting on this assumption, the mine operator successfully implemented a remediation scheme in which the spoil was excavated to intercept the acidic spoil water. The excavation was then re-emplaced with an anoxic limestone drain at its base. The drain now serves both to add alkalinity to the water and to divert the seep to an area where metals can be removed easily via precipitation in wetlands.

Additional Key Words: mine hydrology, mine spoil

Introduction

A great deal of uncertainty and confusion often exists with respect to the origin of contaminated "off-site" seeps which emanate from unmined areas near reclaimed surface mine spoils. The hydrology of the spoil material and surrounding strata is often only poorly understood, and the potential sources of contamination within and/or around the spoil are usually not well-defined. The situation is complicated even further in remining situations or when other surface mines exist on adjacent properties. In these cases, the local hydrology may have already been altered by the previous mining. The consequences of this uncertainty become critical in the context of SMCRA enforcement, where a regulatory agency must make a determination as to whether a mining permit holder is responsible for the remediation of the contaminated off-site discharge.

The degree of uncertainty associated with the origin of an off-site discharge can sometimes be reduced by conducting a preliminary hydrologic investigation at the mine site. While the investigation may still not reveal

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the exact source of the contamination, the information may be sufficient to narrow the differences of opinion which had existed between the permit holder and the regulatory agency. This paper describes how a preliminary hydrologic investigation was used to help a mine operator identfy the potential source of a contaminated off-site seep, implement a cost-effective remediation scheme, and avoid a protracted litigation process.

Mining History

The study site is located in Washington County, Pennsylvania, about 15 miles southwest of Pittsburgh. As shown in Figure 1, the entire Pittsburgh coal seam in the general area had been mined by underground methods prior to 1940. Portions of the deep mine barrier pillar at the Pittsburgh coal outcrop adjacent to the eastern side of the mine permit area had also been strip mined previously during the early 1950's. However, enough coal still remained in the deep mine pillars to allow an economically viable surface mine operation within the permit area shown in Figure 1.

Figure 2 shows the topographic contours and a cross section of the mine permit area prior to the most recent period of surface mining. This mining took place between 1985 and 1990, beginning at the coal outcrop area shown in Figure 2 and progressing to the southwest, southeast,and northwest until the permit boundary or an uneconomic overburden depth was reached. The overburden consisted mostly of shale, with some sandstone. A persistent limestone bed of 5-10 ft thickness was located approximately 40 ft above the Pittsburgh coal. This limestone was believed to be responsible for the alkaline discharges that were produced from remining operations in the vicinity of the study site, despite the fact that the deep mines had discharged acidic water prior to remining. Because of this, the mine operator sought a permit under SMCRA regulations rather than under the Pennsylvania remining program. Therefore, while the subject mine was a remining site in a physical sense, it

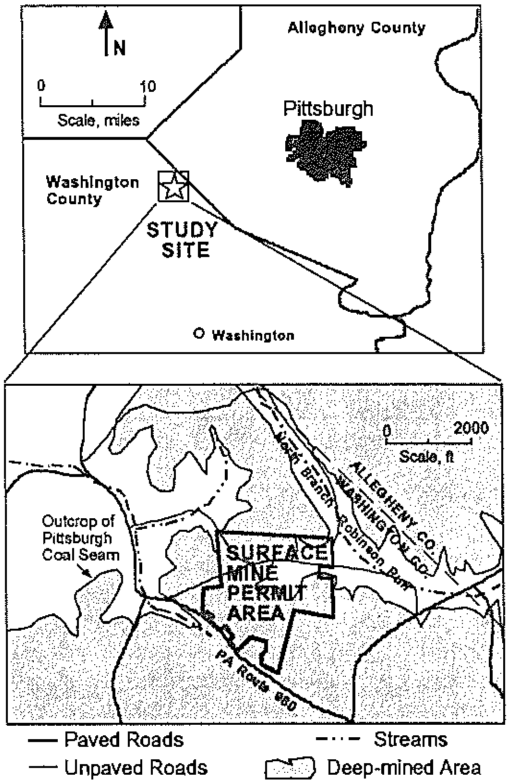

Figure 1. Location Map of Study Site

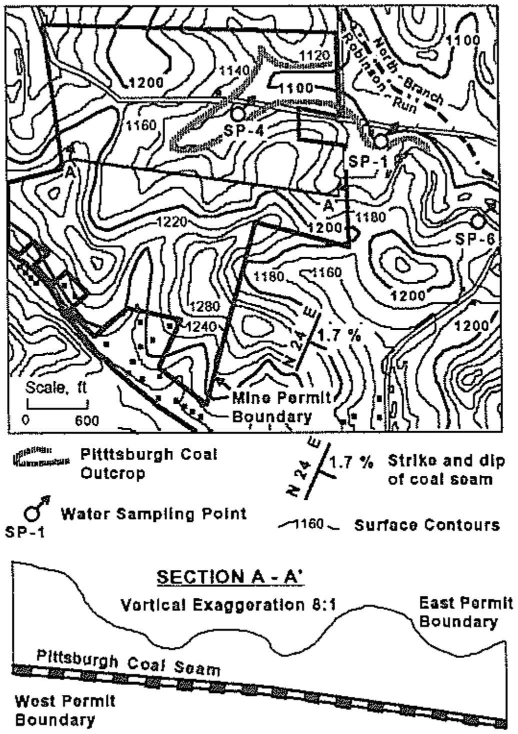

Figure 2. Pre-remining Topography and Sampling Points

was not defined as such in the regulatory arena.

Water Quality Changes

Although no ground water elevation data were available for the 1985-90 period, it can be assumed that the local ground water flow direction was from northwest to southeast due to geologic structure, and was dominated by the presence of the active surface mine and the mined-out Pittsburgh coal seam (see cross-section in Figure 2). Figure 2 also shows the locations of the three surface water sampling points which were closest to the downgradient edge of the mine permit boundary. Sample point SP-4 was intermittent and consisted mostly of surface runoff; it did not show evidence of mining-related contamination before or after the period of mining. Sample point SP-6, located about 1000 ft southeast of the permit boundary, was moderately acidic before, during and after mining. This discharge occurred at the side of a collapsed mine portal structure, and it was obviously connected to a deep mine pool; however, its relationship to the surface mining operation could not be determined. The sampling point of greatest interest was SP-1; prior to mining, this discharge originated as seepage from a swampy area in a natural hollow near the east permit boundary. However, for compliance purposes, sampling was performed at the outlet of a concrete culvert that carried the discharge under the road. Samples were collected on approximately a quarterly basis from 1984 through 1994. Table 1 summarizes the changes in pH, flow rate, and the concentrations of acidity, iron, manganese, and sulfate that occurred at sample point SP-1 before, during, and after the 1985-90 period of surface mining. Note that the discharge was slightly acidic with elevated contaminant levels before mining occurred, and became progressively worse during and after mining. It was unclear whether the source of contamination was the abandoned deep mine workings, the 1950's surface mine spoils just to the east of SP-1, or the new surface mine spoils. Although the discharge did not emanate directly from the surface mine spoil, it was close enough to suggest that a hydrologic connection existed; therefore, the state regulatory agency required the mine operator to initiate treatment of SP-1.

However, the mine operator pointed out that another factor besides the surface mine may have been controlling the degradation of SP-1. At some time shortly after the cessation of surface mining, the landowner to the east of the permitted area made several excavations that began to discharge acidic water at a rate that was greater than that of the original SP-1. Flow from the original SP-1 decreased concurrently. As shown in Figure 3, these post-remining discharges (Seeps A and B) eventually passed through the SP-1 compliance monitoring point. The mine operator contended that the excavations were tapping a portion of the deep mine pool that had not been impacted by surface mining, and that the mining company should not be held responsible for treatment of the discharge.

Initial remediation efforts

The mining company conducted temporary chemical treatment of SP-1 by

Table 1. Water Quality Changes at Sample Point SP-1

Period	# of Samples	Statistic	Flow gpm	Lab pH	Net Acid mg/L CaCO3	Total Fe mg/L	Mn mg/L	Sulfate mg/L
Pre-remining 1/84 - 1/85	6	Median	4.5	5.00	11	0.44	2.85	520
		Mean	5.4	4.78	43	0.76	3.17	527
During remining 1/85 - 1/90	13	Median	1.5	4.90	46	0.90	4.90	790
		Mean	2.2	4.04	132	2.79	4.24	872
After remining 1/90 - 1/94	16	Median	18.0	3.27	111	17.49	10.75	1623
		Mean	20.1	3.24	145	21.49	11.22	1355

placing sodium carbonate briquettes in the contaminated stream; however, this was not viewed as a viable long-term solution by either the company or the regulatory agency. To supplement this treatment, the mining company injected a large quantity of anhydrous ammonia into the abandoned mine voids which were believed to be the source of the discharge. The injection wells, labeled A-1 through A-4 in Figure 3, were located between the surface mine highwall and the mine permit boundary, and penetrated the mine voids within 300 ft of the post-remining seeps. It was expected that the alkalinity and aeration introduced via the ammonia injection would eliminate the acidity of the seeps and cause precipitation of metals to occur within the mine voids. However, the water quality of the discharges showed no appreciable change after ammonia injection, thus causing the mining company to review its approach toward remediation.

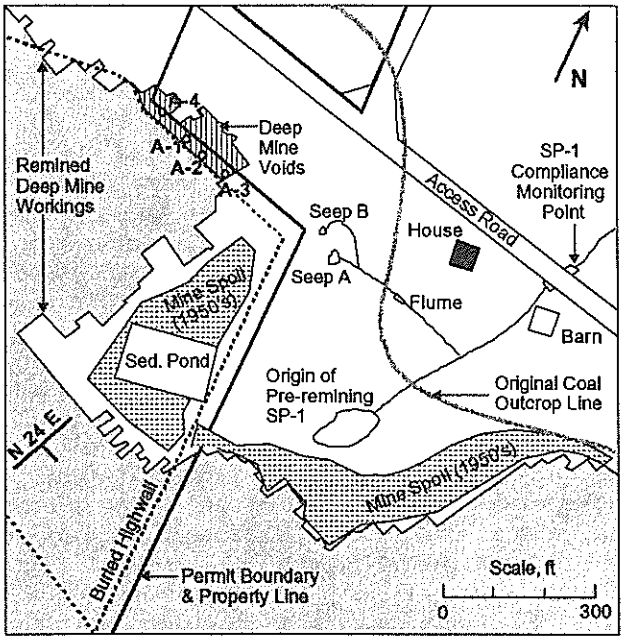

Figure 3.Post-remining Discharge Area

Hydrologic Investigation

During January 1994, the mining company agreed to cooperate in a preliminary hydrologic investigation at the site, with the intent of determining why the initial ammonia injection had failed, and whether the desired remediation could be achieved by injecting cement kiln dust into the abandoned deep mine voids. The following sections describe the data collected and analyzed by the U. S. Bureau of Mines in support of this effort.

Preliminary Data Collection

Water elevations in the mine void wells were measured weekly from March through June of 1994; the combined flow rate of Seeps A and B was also measured weekly with an H-type flume (Figure 3). Water quality samples were collected once every two weeks from the void wells and the seeps during the same period. Site conditions precluded the direct measurement of the flow rates of these seeps, but estimates were obtained via ion mass-balance methods described previously by Aljoe (1995). Concurrently with these efforts, a chemical tracer test was conducted by injecting a concentrated sodium bromide solution into two of the four ammonia injection wells. The following sections describe the results of these investigations.

Water Elevations and Flow Rates. Water elevations in wells A-1, A-2, and A-3 were almost identical (Figure 4), suggesting that these wells penetrated the same mine pool. The mine voids were only partially flooded, with about 2 ft. of water in a void height of about 7 ft. By June 14, the mine void at Well A-1 became dry. It was inferred that a small mine pool existed in the voids penetrated by these three wells, and that the pool was drained by a consistent discharge source.

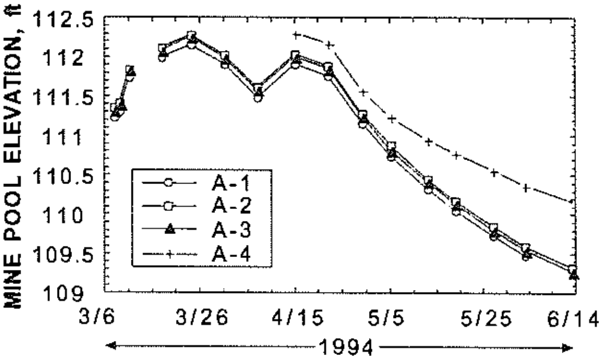

Figure 4. Water Elevations in Mine Void Wells (arbitrary reference datum).

The water elevation in Well A-4 was consistently higher than in the other three mine void wells by 0.5 to 1.0 ft; this difference was considerably greater than the error that could be attributed to surveying and level measurement. Also, the decline in the water elevation at Well A-4 was less steep than in the other three wells during May and June 1994. From these data, it was inferred that another small mine pool existed in the portion of the deep mine penetrated by well A-4. The degree of hydrologic connection between the two pools could not be confirmed; however, the behavior of Well A-4 during May and June suggested that this pool was not directly connected to the same discharge source as the pool penetrated by the other three wells.

The combined flow rate from seeps A and B was directly related to the elevation of the mine pool at wells A-1, A-2, and A-3 (Figure 5). This relationship was not surprising, given that both the pool elevation and flow rate would be similarly influenced by precipitation. Figure 5 shows that the mathematical relationship at this site was exponential (linear plot on log scale); however, mine pool elevation-discharge plots at other sites had exhibited a direct linear relationship (Aljoe, 1994).

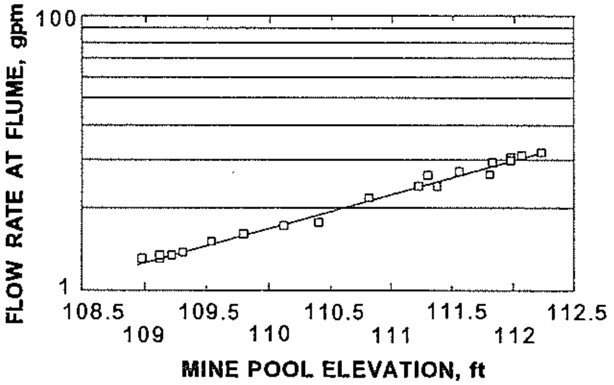

Figure 5. Mine Pool Elevation vs. Discharge Rate.

Another deviation from past experience was that the total discharge rate, about 30 gal/min for much of the study period, was much larger than would be expected from such a small postulated recharge area (about 2/3 acre of surface area above the mine voids). The lack of a visible physical connection between the seeps and the mine voids also suggested that more evidence had to be gathered to verify the hydrologic connection between the mine pool and the contaminated seeps.

Tracer Test. One of the most direct ways to verify the hydrologic connection was to inject a chemical tracer into the mine voids and monitor the seeps for its arrival. The bromide ion was chosen as the tracer because of its conservative behavior in mine waters, the lack of detectable bromide concentrations in the mine voids and the seeps, and the ease of application in the form of a concentrated bromide salt solution. On March 8, 1994, a total of 6.0 kg of NaBr salt (4658 g of Br^-) was added to the mine voids; half of this total was added to Well A-1, and the other half to well A-3. These wells were chosen because Well A-2 still possessed large quantities of ammonia and Well A-4 had not been found at the time the tracer test was begun. If the extent of the pool were limited to the area occupied by the mine voids (approx. 433,000 gal), this amount of bromide would have been sufficient to raise the bromide concentration in the mine pool to a level that was about 15 times the laboratory detection limit of 0.1 mg/L, even if the solute became uniformly distributed within the pool. This ensured that if the mine pool and seeps were indeed hydrologically connected, bromide would be detected at the seeps even if a substantial degree of dilution were occurring.

In general, the results of the tracer test showed that there was a distinct hydrologic connection between the mine pool and the seeps, but that the connection was not as direct or exclusive as first anticipated. Figure 6 shows the bromide concentrations (a) and loads (b) at the three discharge locations. If the mine pool were indeed the only source of water to the seeps, the high discharge rate would result in a pool turnover time (complete passage of the tracer cloud through the seeps) of about 10 days. However, the peak bromide cncentration did not occur until the twelfth day, and the total time required for the bulk of the tracer to pass through the seeps was about 50 days. This suggested that one or both of the initial assumptions about the flow system was incorrect, i.e., the mine pool was much larger than the area of open mine voids, and/or the monitored portion of the pool was not the only source of water to the seeps.

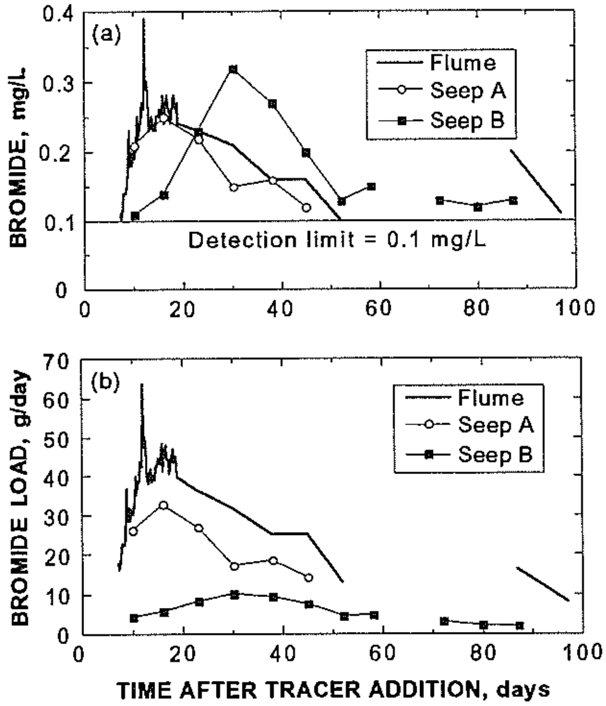

Figure 6. Results of Bromide Tracer Test (a) concentrations; (b) loads.

From the peak bromide concentration and load shown in Figure 6, the average flow velocity from the bromide injection wells to the seeps was estimated to be 12 to 27 ft/day. This velocity is more than an order of magnitude lower than found by Aldous and Smart (1988) for underground mine workings with pure conduit-type flow. Instead, the velocity is closer to those for sealed underground mine workings (Aljoe and Hawkins, 1993), mine spoil (Hawkins and Aljoe, 1992), or glacial sediments (Grisak, et al., 1977). These results suggested that the tracer cloud moved through relatively resistive material (mine spoil and/or unmined, fractured strata) between the injection wells and the seeps.

Analysis of tracer data gathered weekly from the injection wells and seeps showed that the mine pool was hydrologically connected to both seeps, but the degree of connection was different for each seep. Seep A, which consistently accounted for 75% to 80% of the flow at the flume, also appeared to be the most direct outlet for the mine pool. As shown in figure 6, the bromide profiles of Seep A generally paralleled those of the flume, and the bromide load at Seep A was generally greater than at Seep B. Higher bromide concentrations were often found at Seep B, but the path from the mine voids to Seep B appeared to be less direct. The peak concentration occurred two weeks later than at Seep A; Seep B also had a less-pronounced loading peak, and concentrations at Seep B remained detectable until almost 90 days after the test was begun. This suggested a slower, more evenly distributed release of tracer through Seep B.

Figure 7 shows the bromide concentrations in the injection wells over the sampling period, along with the flume concentration curve. The consistently lower concentrations in Well A-3 were attributed to the greater amount of flushing water that had been used in this well. The rates of concentration decline in the two wells were very similar, but the higher initial concentration in Well A-1 allowed bromide to remain detectable until the mine void became dry.

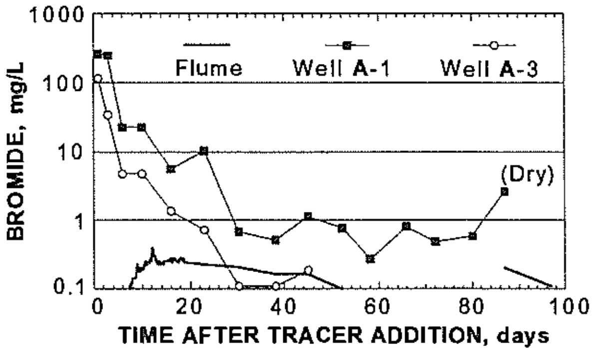

Figure 7. Tracer concentrations in Mine Pool and Discharge.

The fact that bromide concentrations in part of the mine pool were on the order of 1 mg/L while seep concentrations were undetectable indicated that dilution was occurring between the mine voids and the seeps.

Water Quality Data. Initial water quality data collected at the site showed that the most critical difference between the water quality in the monitoring wells and the seeps was the net acidity over the study period, as depicted in Figure 8.

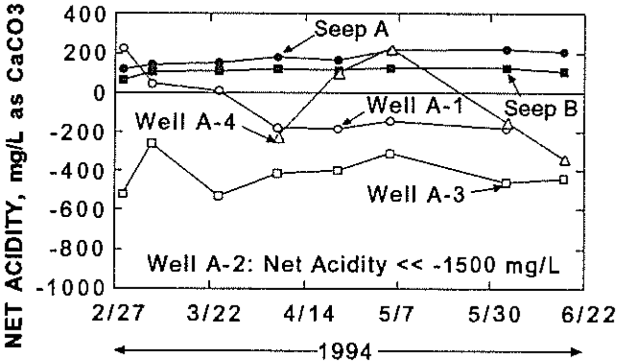

Figure 8. Net Acidity in Mine Pool and Seeps.

Net acidity at the seeps was very stable at 100 - 200 mg/L over the study period; conversely, the mine voids generally possessed strongly alkaline water (negative net acidity = net alkalinity). Although wells A-1 and A-4 were acidic on several occasions, they showed temporal fluctuations that contrasted markedly with the stable pattern of the seeps. Furthermore, Well A-3, which was closest to the seeps and was shown to be hydologically connected to the seeps via the tracer test, was consistently net alkaline by more than 400 mg/L. In order for the seeps to be net acidic, while still receiving recharge from the alkaline mine pool (as verified in the tracer test), one or both of the following must have been occurring: (1) significant geochemical changes were occurring along the flow path; or (2) another source of recharge that was more acidic and probably larger in volume than the mine pool was present.

Table 2 lists the average values of the other important mine water quality parameters over the study period, along with the average cation/anion ratios calculated from the laboratory analyses. The substantial differences in water quality within the mine voids and the lack of tracer detection in wells A-2 and A-4 suggested that there was very little geochemical mass transfer within the mine pool. It would therefore be inappropriate to combine the parameter values across different wells to obtain "average" values for the pool as a whole. In fact, it may be justifiable to exclude Well A-2 completely from the analysis; its anomalous characteristics were attributed to the continued presence of ammonia from the previous injection. Water samples were not routinely analyzed for ammonia; however, the presence of ammonia (as the NH_4^+ cation) was suspected when the very low cation/anion ratio of Well A-2 (see Table 2) was first noted. Several subsequent samples from Well A-2 were found to contain ammonia concentrations of greater than 1000 mg/L. The cation/anion ratio of Well A-3 was also significantly lower than unity, so it is possible (though not verified by laboratory analysis) that ammonia was

Table 2. Average Water Quality Parameters, March - June 1994

Location	pH	Fe, mg/L	Ca, mg/L	Mg, mg/L	Al, mg/L	Na, mg/L	Mn, mg/L	SO4, mg/L	Cations /Anions	Notes
SEEP A	4.37	43.0	324	133	6.0	19.2	13.2	1483	1.00	
SEEP B	3.62	20.2	370	170	20.8	12.6	16.4	1903	0.93	
Well A-1	6.68	73.0	528	227	5.7	17.6	14.4	2203	1.03	Tracer Inj.
Well A-2	8.40	0.8	98	150	0.1	22.7	1.3	2999	0.13	High NH3
Well A-3	6.67	7.7	459	191	0.9	21.2	13.4	2188	0.75	Tracer Inj.
Well A-4	6.40	198.0	532	267	4.4	14.6	21.4	2654	0.97	

also partially responsible for its alkaline character. However, wells A-1 and A-4 had cation/anion ratios near unity even when they were net alkaline, indicating that ammonia concentrations were very low. Therefore, except for Well A-2, it was concluded that the ammonia injection alone was not responsible for the predominantly alkaline character of the mine pool.

Some of the water quality differences shown in Table 2 could have resulted from geochemical reactions along the flow path from the wells to the seeps; however, these reactions alone cannot explain all the differences. For example, the pH and iron concentrations were generally higher in the wells than at the seeps, while the aluminum concentrations were lower. There were also significant decreases in net acidity (Figure 8), calcium, magnesium, and sulfate. Magnesium in mine drainage has been found to be particularly conservative in almost all situations (Hedin, et al., 1994); calcium and sulfate would also be expected to be conservative under these site conditions (Bencala, et al., 1987). The most reasonable explanation for these decreases would be dilution by other recharge sources whose concentrations of these ions were lower.

Additional Data from Spoil Wells

Given the results described above, it was clear that the mine voids and seeps were hydrologically connected, but that the flow rate and water quality of the seeps were heavily influenced by one or more other sources. The most likely other source was the mine spoil; however, in the initial analysis, no hydrologic data were available for the spoil. In order to investigate this possibility, the mining company installed four monitoring wells in the spoil (Wells B-1 through B-4) as shown in Figure 9. Water level and water quality data were collected from the spoil wells for a short period after their installation (from June 17 through August 9, 1994). Slug injection tests were performed to determine the relative hydraulic conductivity of the spoil at the well locations. Longer-term data from these wells were not collected. However, the initial data generally supported the conclusion that ground water in the spoil was contributing to the seep discharges, and formed the basis of the coal company's subsequent remediation effort.

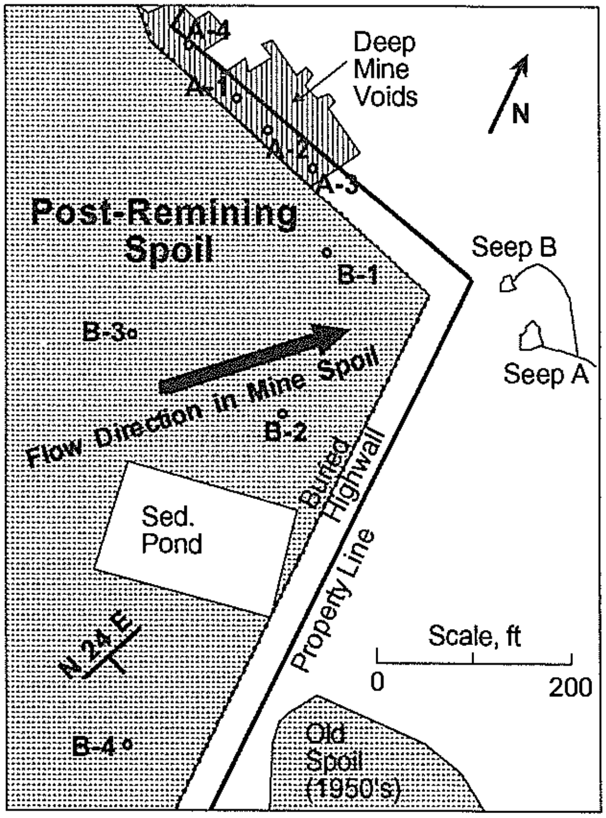

Figure 9. Mine Spoil Well Locations.

The water level in the monitored mine pool was about the same as that of Well B-3, and about 0.5 to 1.0 ft above the levels in wells B-2 and B-1. The water elevation in Well B-4 was 3 to 4 ft below those of the other wells; however, because of its physical separation from the other wells and the seep areas, and the tendency of mine spoil to have multiple flow paths, Well B-4 was considered to be relatively unimportant to the flow system in the seep area. Figure 9 shows the local ground water flow direction as determined from the water levels in wells B-1, B-2, and B-3. Note that the flow direction did not parallel the dip of the pit floor, but was directed toward the seeps.

Table 3. Average Water Quality Parameters, June - August 1994

Location	pH	Net Acid, mg/L CaCO3	Fe, mg/L	Ca, mg/L	Mg, mg/L	Al, mg/L	Na, mg/L	Mn, mg/L	SO4, mg/L	Cations /Anions
SEEP A	4.82	95	52.5	403	170	2.95	23.86	13.25	1788	1.01
SEEP B	3.55	186	41.5	446	216	15.44	14.58	16.10	2207	0.97
Mine Void Wells										
Well A-2	7.29	-2685	0.2	162	167	<0.1	18.44	1.65	2116	0.24
Well A-3	6.56	-422	3.6	496	208	<0.1	19.71	13.63	2141	0.82
Well A-4	6.65	-419	158.1	479	239	<0.1	14.78	18.77	2497	0.85
Spoil Wells										
Well B-1	5.86	-89	84.9	555	213	0.56	26.33	18.41	2091	1.12
Well B-2	**4.28**	**52**	**66.9**	**382**	**153**	**0.72**	**30.18**	**12.57**	**1617**	**1.09**
Well B-3	6.64	-152	89.6	647	211	0.11	31.73	17.34	2111	1.18
Well B-4	7.19	-284	1.2	346	75	1.07	34.85	2.36	878	1.05

Table 3 summarizes the water quality data (average of 2 to 4 samples per well) collected during the study period after the spoil wells were installed. Like the mine voids, the spoil contained primarily alkaline water at the well locations. However, the well closest to the seep area (Well B-2) contained water that was consistently net acidic; although the concentration of acidity was not as great as that of the seeps, it confirmed that acidic water was indeed present in the spoil. Furthermore, the concentrations of the calcium, magnesium, and sulfate in Well B-2 were lower than those of the seeps, as would be expected if the mixing scenario postulated above were taking place.

Table 4 summarizes the hydraulic conductivity data collected from slug injection tests in the spoil wells. As would be expected for mine spoil, the hydraulic conductivity values had a broad range; the hydraulic conductivities of the wells closest to the seep area (B-1 and B-2) were more than an order of magnitude greater than those of the other two wells. Although the range of influence of a slug test is not large (on the order of a few feet), the fact that the hydraulic conductivity of the acidic well (B-2) was the greatest suggested that it could lie along or near a preferred flow path for acidic water originating in other parts of the spoil and/or the undisturbed deep mine workings upgradient of the remined area.

Table 4. Hydraulic Conductivity of Mine Spoil Wells

Well	Hydraulic Conductivity, ft/sec
B-1	3.91E-04
B-2	6.12E-04
B-3	3.28E-05
B-4	9.27E-08

Conceptual Description of Flow System

While the data collected in the hydrologic investigation were far from conclusive, a preliminary conceptual description of the flow system at the site was developed from the available data. Given the high carbonate content of the mine overburden, the most likely source of the acidic water at the seeps was the large undisturbed portion of the abandoned deep mine workings outside the remined area (see Figures 1 and 3). Recharge from the mine voids to the spoil could occur either from unflooded workings northwest (upgradient) of the spoil, or lateral (along strike) inflow from a large mine pool to the southwest of the mine permit area. Existence of such a mine pool could be inferred from the large, consistent, acidic discharge at SP-6 (see figure 2). Under "normal" conditions, the resistance to flow of the mine spoil and the undisturbed material at the eastern edge of the remining permit boundary would have been much less than that of the areas where the mine voids were very close to the surface (such as at SP-6). As such, very little flow would be expected at the east permit boundary. However, the excavations made by the landowner could have decreased the overall resistance to flow in that area. Under these conditions, acidic water that entered the spoil from the deep mine could have passed relatively quickly, and without much chemical alteration, through large conduits that commonly exist in spoil to emerge at Seeps A and B.

The predominantly alkaline character and associated ion concentrations of the water in the mine spoil and void wells (except for the influence of ammonia in well A-2, as discussed earlier) were indicative of mine drainage that had been neutralized by calcium carbonate. Under the flow scenario described above, much of the recharging water would follow a comparatively direct path to the seeps, with relatively little modification of water quality resulting from its contact with the alkaline mine spoil. The water quality of Well B-2 may be indicative of a portion of the spoil that is relatively close to one of these conduits. Another percentage of the inflowing water would follow a more circuitous path to the seeps; the pH and alkalinity of the water would increase in proportion to the contact time with the alkaline spoil. Calcium and perhaps magnesium concentrations would increase, while other indicators of mine drainage contamination (sulfate and manganese) would remain high. The behavior of iron would be much more complex; for example, ferrous iron in the mine water would be relatively unaffected by passage through the alkaline spoil under anoxic conditions. However, ferrous iron that oxidized to the ferric state would precipitate immediately due to the high pH conditions. Water that entered the small pocket of mine voids at wells A-1 through A-4 could "pool" in this area prior to exiting through the seeps via the unmined strata and/or the spoil in the vicinity of Well B-1.

Remediation Efforts

The results of the hydrologic investigation indicated that although the evidence was not clear-cut (i.e., a source of water of extremely acidic character was not positively identified) the the acidic water at the seeps was almost certainly passing through the mine spoil. Conditions of the mining permit dictated that since the seeps were hydrologically connected to the mine spoil, the discharges had to be treated to SMCRA effluent standards. Since the acidic quality of the seeps probably resulted from the lack of sufficient contact time between the mine water and the alkaline spoil material, treatment of the seeps via an anoxic limestone drain (ALD) was chosen. In January 1995, the mining company excavated a trench within the spoil (Figure 10) to intercept the inferred area of acidic water, and installed an ALD along the base of the old pit floor.

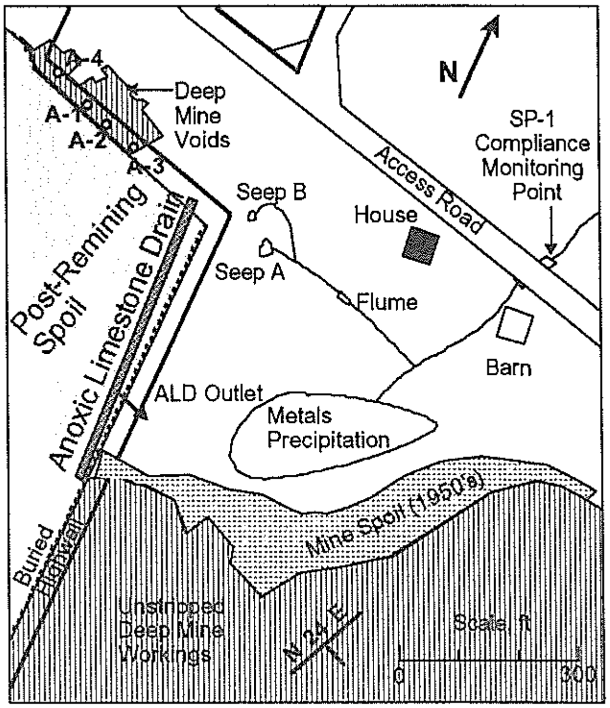

Figure 10. Location of Anoxic Limestone Drain in Remined Spoil.

This approach was considered to be technically feasible because the iron at the flume location was almost entirely in the unoxidized (ferrous) state, and the aluminum concentrations were not excessive. Furthermore, permission of the adjacent landowner was not required for this activity because it took place within the original permit boundary.

As the excavation of the trench progressed northward, flow rates from the trench increased suddenly to several hundred gallons per minute. This suggested that water had pooled in the spoil, and was released as the primary storage conduit(s) were intercepted by the trench. Flow rates remained very high for almost a week before decreasing to the rate that existed before the excavation began (about 15-20 gpm). The bottom of the 500 ft long, 12 ft wide trench was filled with 500 tons of limestone (bed depth approx. 2 ft). Piping was installed above the limestone to allow it to remain inundated while diverting the discharge away from seeps A and B. The drain pipe discharged into the swampy area of the original SP-1, where sufficient space for precipitation of metals was available. After backfilling of the trench was completed, discharge from the ALD outlet pipe continued while flow from seeps A and B ceased. Flow rates from the ALD were not measured; however, visual estimates by both the state inspector and the mine operator indicated that the flow was about the same as that of the seeps prior to construction of the ALD.

Table 5 summarizes the water quality data at the ALD outlet and SP-1 during the 5-month period after the drain was completed. As expected, alkalinity concentrations at the ALD outlet were consistently greater than 100 mg/L. Iron concentrations were lower in the ALD outlet than in the spoil wells during the previous year (Table 3), suggesting that iron may have been precipitating in the ALD. There were no concurrent spoil well data to compare to those in Table 5, however, so this could not be concluded definitively. It was clear that almost all of the iron leaving the ALD was being precipitated prior to reaching SP-1. It also appeared that significant amounts of manganese were being precipitated; this is consistent with the results of Hedin, et al. (1994) which indicate that manganese can be removed in wetland systems if ferrous iron concentrations are very low.

Discussion

The remediation effort described above, which appears to be successful thus far, may not have been attempted without the additional knowledge gained through the hydrologic investigation. When the contaminated off-site seeps first occurred, there was a substantial difference of opinion between the mine operator and the regulatory agency with respect to the origin of the seeps and the responsibility for their abatement. At first, the investigation yielded results that were somewhat contradictory. Although a chemical tracer test confirmed the hydrologic connection between the seeps and a portion of abandoned deep mine workings that were not disturbed by the mineoperator's remining efforts, other hydrologic and water quality data

Table 5. Water Quality Parameters after ALD Installation, March - August 1995

Location	# of Samples	Statistic	pH	Total Alk. mg/L CaCO3	Net Acid mg/L CaCO3	Fe mg/L	Al mg/L	Mn mg/L	SO4 mg/L
Anoxic drain outlet	16	Mean	6.28	172	4	20.85	1.48	10.33	1506
		Median	6.25	174	0	17.45	0.93	10.55	1511
Culvert outlet SP-1	11	Mean	7.49	208	0	0.99	0.64	4.48	1336
		Median	7.50	146	0	0.42	0.50	5.67	1331

Alkalinity values in this table are total alkalinities; they are not directly comparable to the "negative net acidities" shown in Table 3 and Figure 8 because of differences in laboratory measurement procedures suggested that the seeps were influenced more heavily by other sources that had not yet been identified. This explained the failure of the mine operator's initial remediation effort and discouraged further remedial efforts involving the abandoned mine voids. Further investigation revealed that the ground water in the mine spoil was somewhat acidic; this was in direct contrast to the mine operator's experience at several other remining sites in the same area. The degree of acidity found in the spoil water was not as severe as that of the seeps, but the hydrologic and water quality data were sufficient to convince the mine operator that remedial measures would have to be taken. The mine operator used the available data to implemement a remediation scheme which involved re-excavating the spoil to intercept the acidic water and routing the water through a passive treatment system (ALD and wetlands). Through these efforts, a situation which could have resulted in lengthy litigation and a legally enforced, inefficient temporary treatment scheme was resolved by a relatively cost-effective, long-term treatment system.

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