INVESTIGATION AND CHARACTERIZATION OF GROUNDWATER FLOW SYSTEMS IN ABANDONED UNDERGROUND COAL MINES[1]

by

William W. Aljoe
and
Jay W. Hawkins[2]

Abstract. Surface coal mines often face operational or environmental problems when located in close proximity to flooded, abandoned underground mines. A basic understanding of the groundwater flow systems within abandoned mine pools may help surface mine operators assess the probable hydrologic consequences of their operations or evaluate in-situ water quality improvement techniques. Substantially different mine pool flow systems were found at two acid-producing, abandoned underground mines in western Pennsylvania. Mine maps, surface observations, discharge rates, precipitation records, water levels in monitoring wells, and water quality analyses were used to characterize the systems. At one site, the mine pool piezometric surface was horizontal, and most of the mine pool flow occurred through open entries at the base of the system. Water quality analyses and tracer tests indicated that flow was probably not uniform through all mine entries, and that flow through monitored entries was relatively slow. At the second site, water levels in monitoring wells showed a distinct water table gradient. This indicated the presence of diffuse flow through caved entries. However, the water flowing from the monitored section of the mine pool may have represented only a small portion of the total flow at the two monitored discharge points. A tracer test revealed a strong hydrologic connection between the tracer injection well and one downgradient well, but the tracer was not detected at the main discharge 6 months after injection. A more detailed assessment of the mine pool hydrology at the second site was not made because of the suspected large size of the pool and the effect of multiple discharges on pool behavior.

Additional key words: mine hydrology, mine pools, acid mine drainage

Introduction

Surface coal mine operations are frequently performed on properties that contain abandoned underground mines. Special problems occur when abandoned mines discharge water at the surface or contain pooled water. Obviously, operational problems can occur if the surface mine intercepts or comes close to a flooded portion of the deep mine. More importantly, under the

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[2]William W. Aljoe is a Mining Engineer and Jay W. Hawkins is a Hydrologist with the U.S. Bureau of Mines, Pittsburgh, PA 15236

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Surface Mine Control and Reclamation Act, surface mine operators are held completely liable for all deep mine discharges that are affected by their operations, as determined by the state or Federal regulatory authority. If the deep mine discharge is of poor quality (e. g., acidic), as is often the case in the eastern U.S., the cost of controlling and treating the discharge can be so expensive that the economic viability of the entire surface-mining operation may be jeopardized. Indeed, a surface mine permit may not be granted if the regulatory authority determines that unacceptable post-mining water quality of the deep mine discharge will occur.

A thorough understanding of mine pool hydrology, including knowledge of flow paths and pool turnover rate, is critical to the success of any water-quality improvement technique, such as addition of alkalinity to the overburden or the mine pool itself. Toward this end, the U. S. Bureau of Mines performed hydrologic studies of two "typical" acid mine pools in western Pennsylvania. The study sites were located at Keystone State Park, near Latrobe, Pennsylvania, and Friendship Hill National Historic Site, near Uniontown, Pennsylvania (Figure 1).

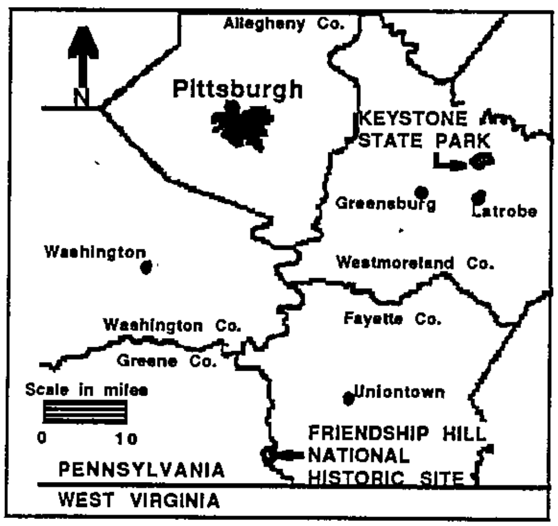

Figure 1. Locations of mine pool hydrologic study sites.

The near-term purpose of these studies was to gather the hydrologic data needed to assess the feasibility of abating acidic discharges from the mines by injection of alkaline solutions into the mine pools. During the studies, it became evident that the hydrologic characterization of abandoned underground mine pools could be of use in a more general context. Therefore, this paper focuses on the hydrology of the mine pools; of special interest is the vast difference between the fundamental hydrologic characteristics of the two pools. A more complete discussion of the experimental alkaline injection treatment is provided elsewhere (Aljoe and Hawkins 1991). The hydrologic investigations at the Keystone and Friendship Hill sites consisted of: (1) monitoring of mine discharge flow rates and quality; (2) drilling and installation of mine pool monitoring wells; (3) monitoring and interpretation of water levels and water quality in the wells; (4) examination of the response of the mine pools to precipitation; and (5) tracer tests to determine mine pool flow rates, flow paths, and pool volume turnover time. The subsequent application of alkaline injection at the Keystone State Park site also provided useful information about the hydrology of this mine pool.

Hydrologic Study - Keystone State Park

One of the greatest advantages of the Keystone site was that its history was relatively well-documented compared to most abandoned mine sites. The primary sources of information were a report on an attempt to seal one of the mine portals (Chung 1973) and a 1941 mine map that contained mine floor elevations. Documentation of subsequent mine reclamation projects was obtained from the Pennsylvania Department of Environmental Resources, Bureau of Abandoned Mine Reclamation, and Keystone Park personnel.

Site Background

The mine at Keystone State Park, which was originally known as the Salem No. 2 mine of the Atlantic Crushed Coke Co., was developed in the Upper Freeport coal seam using room-and-pillar methods. The total undermined area was approximately 300 acres. The mine maps and the absence of surface subsidence indicated that pillars were not removed in the vicinity of the mine portals, although pillars may have been removed elsewhere in the mine. Figure 2 illustrates the general geologic structure in the vicinity of the Keystone site (strike N 76° E, dip approx. 2° NW). Most of the mine workings are situated on the northwest limb of the Fayette Anticline, although southeast portions of the mine cross the anticlinal axis.

As shown in Figure 3, the main portals of the mine were located at the lowest structural point of the coal seam. When the abandoned mine portals were sealed in the early 1970s, water began to build up in the mine behind the seals. Eventually, the hydraulic pressure of the mine pool became sufficient to force the water to the surface approximately 150 ft behind the portal seals. A borehole was installed to relieve the pressure and route the water through a pipe network to a surface stream about 250 ft away. This free-drain condition allows relative equilibrium between recharge and discharge, so the mine pool level fluctuates only slightly over time.

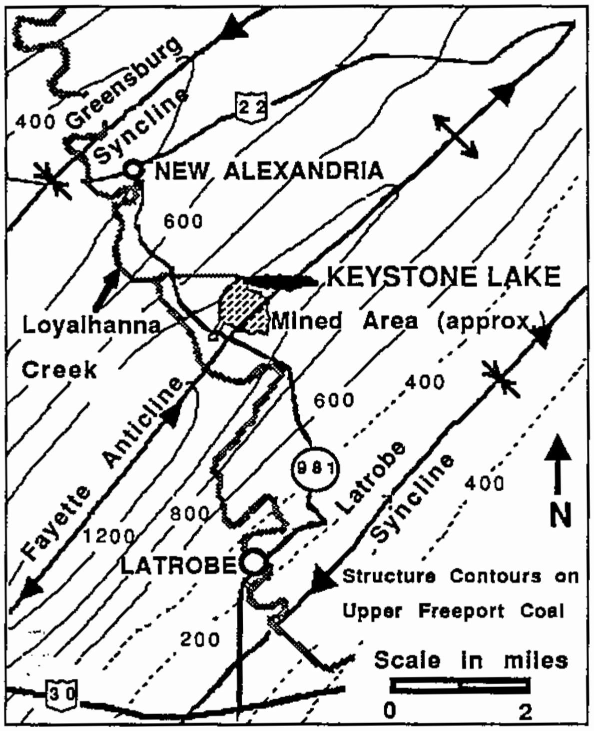

Figure 2. Geologic structure in the vicinity of the Keystone site.

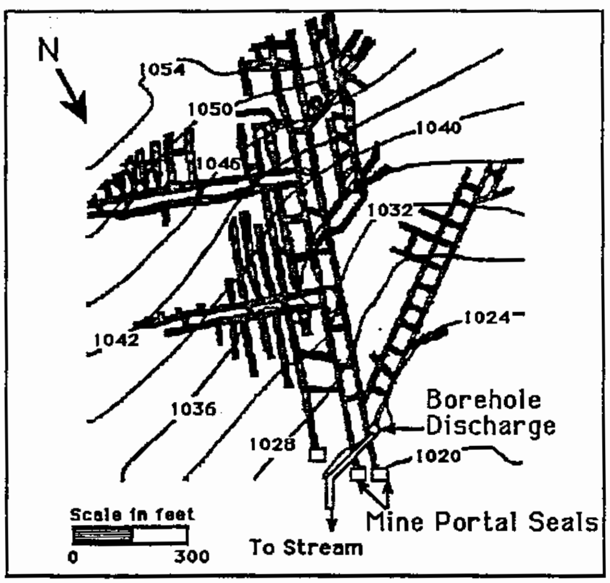

Figure 3. Mine floor structure contours near Keystone mine portal area.

Mine Pool Size Estimate. During the mine sealing effort, a steel-cased vent hole was installed approximately 250 ft behind the portal area. The vent hole apparently did not penetrate a mine entry, but was hydrologically connected to the mine pool. The elevation of the mine pool as measured in the vent hole was approximately 29 to 33 ft above the mine floor elevation at the portal seals, or 1,047 to 1,050 ft above sea level (see Figure 4). At these elevations, the flooded area was approximately 10 acres; assuming an extraction ratio of 50 %, the pool volume was estimated to be 23 to 26 million gallons.

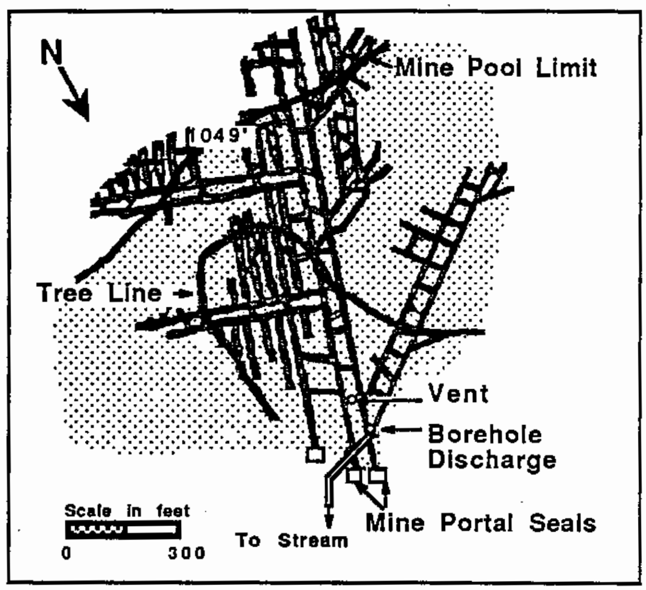

Figure 4. Limits of mine pool at Keystone site.

Monitoring Wells. To prevent damage to Keystone Park property, well drilling was limited to the north side of the tree line shown in Figure 4. Efforts were made to place most of the wells in main entries of the mine, since these were most likely to have been well-supported and thus remain open to serve as preferred flow paths for the mine pool. Lack of precise correlation between the mine map and existing surface features limited the accuracy of these efforts. As shown in Figure 5, five of the monitoring wells encountered open mine voids; three were located in a main entry (wells 1, 2, and 6), one was in a submain (well 3) and one was in a room entry (well 8). Four wells penetrated solid coal (wells 4, 5, 7, and 9). All holes were 6-1/4 in diameter and cased with 4 in diameter PVC pipe. In void wells, the annulus between the casing and hole was grouted from the top of the mine void to the land surface. In wells penetrating coal, 10-ft screens with sand packs were installed through the coal and isolated from the grout by a 2-ft layer of bentonite.

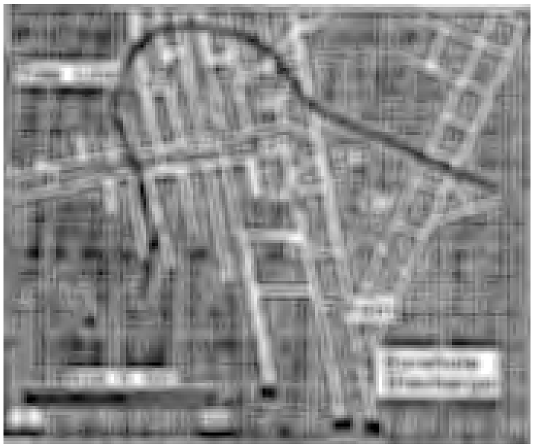

Figure 5. Locations of mine pool monitoring wells at Keystone site.

Mine Pool Hydrology

Unlike most groundwater systems, which have regular, lateral hydraulic potential gradients that govern the rate and direction of flow, the Keystone mine pool had a horizontal piezometric surface, (i.e., water levels in all void wells were the same). Figure 6 is a cross-section of the Keystone site showing the conceptual pool flow system. This system is analogous to a surface water reservoir with an underdrain discharge; flow occurs because the drains (mine voids) are open to the atmosphere (discharge borehole) at an elevation that is somewhat lower than that of the pool surface.

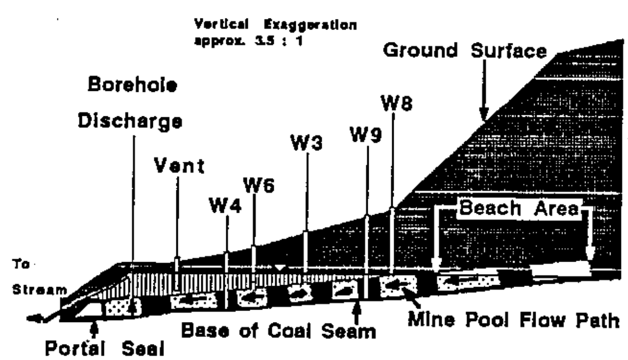

Figure 6. Cross-section through wellfield, Keystone site.

Lateral flow occurs primarily through the open mine entries at the base of the system, in a direction generally perpendicular to the geologic structure contours due to the location of the discharge borehole. Flow through the saturated overburden is downward toward the voids. The absence of surface subsidence and the fact that no caved conditions were encountered during drilling suggested that all voids remained completely open and were equally likely to serve as conduits for mine pool flow.

Mine Discharge Flow Rates and Pool Levels. Mine discharge flow rates were measured at least twice weekly for a period of more than one year. The measured flow rates varied widely (from 7 to 156 gal/min) with a mean of 54, standard deviation of 29, and median of 47 gal/min. Mine pool elevations were measured at least weekly throughout the study period. The average mine pool elevation showed little variation, fluctuating over a range of only 1.66 ft; however, a strong linear correlation was found between pool elevation and discharge flow rate. Figure 7 shows that the pool elevation and discharge flow rate rose and fell together throughout the study period, while Figure 8 clearly illustrates the strong linear correlation (R_{xy}= 0.947). This functional relationship is to be expected, and is determined by both the head in the mine pool and the conditions at the discharge borehole.

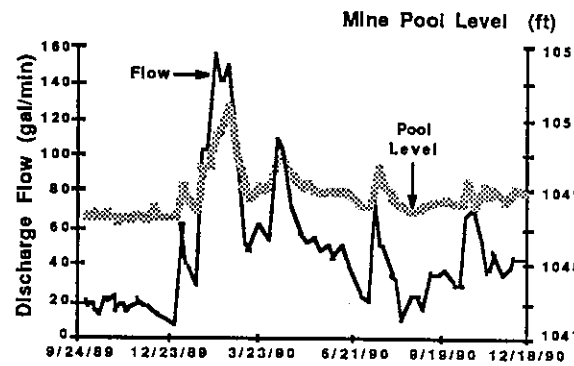

Figure 7. Mine pool levels and discharge flows at Keystone site.

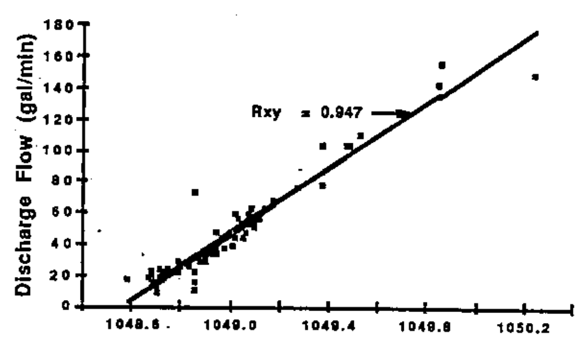

Figure 8. Linear regression - mine pool level vs. discharge flow rate, Keystone Site.

Response to Precipitation. Rainfall data were obtained from a permanent weather station approximately 5 miles from the Keystone site. Figure 9 shows how the discharge flow rate responded to rainfall during the first 11 months of the study period (October 1989 through August 1990). Because of the linear relationship between the mine pool level and discharge flow (Figure 8), response of the mine pool level to rainfall exhibited a similar pattern. However, discharge flows were chosen to represent the overall pool response in Figure 9 and in the following discussion because of the higher magnitude of flow response and greater density of flow data.

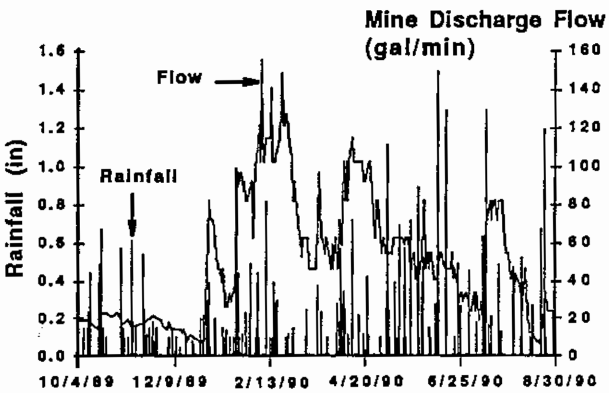

Figure 9. Response of Keystone mine pool to rainfall, October 1989 to August 1990.

In general, response of the mine pool to applied rainfall was much greater during winter and spring than in summer and fall. Note in Figure 9 that the pool did not respond significantly to five very large precipitation events that occurred between October 4 and November 19, 1989. At this time of year, two factors may have served to limit deep infiltration and mine pool recharge. First, the moisture-retaining capacity of the surface soils, subsoils, and fractures in the unsaturated overburden would have been relatively high because of low rainfall and high rates of evapotranspiration during the summer and early fall. Most of the precipitation that infiltrated the surface would serve to resaturate the soil and overburden. Conversely, a large, rapid pool response coincided with a rainfall/snowmelt period from December 26, 1989 through January 2, 1990, despite the fact that this event was no larger than those that had occurred during the fall. It is believed that a series of small rainfall and snowfall events during late November and December, 1989, along with lower evapotranspiration rates during this period, may have allowed the moisture the soil and the walls of overburden fractures to reach field capacity. The onset of additional precipitation and infiltration would then cause rapid recharge to the mine pool and subsequent pool response.

Between January 2, and January 17, 1990, the pool flows and levels declined steadily despite the occurrence of several small precipitation events. Although the overburden probably remained saturated during this period, the low precipitation rates and frozen ground conditions may not have permitted significant amounts of infiltration. However, the next significant precipitation event (January 18-22) was accompanied by another large, rapid pool response. From January 22 through February 21, a fairly steady series of precipitation events was accompanied by a consistent increase in flow and pool level, with localized flow peaks occurring shortly after each precipitation event. This behavior suggests that the overburden was completely saturated and pool recharge rates were at a maximum; note that the maximum flow values for the study period were recorded at this time.

Pool levels and flow rates declined steadily from February 21 through the end of March 1990, although flow again showed several localized peaks that coincided with small rainfall events. Longer days and new plant activity during this time may have resulted in increased evapotranspiration and decreased moisture content of the soil and overburden. Note in Figure 9 that the frequency, duration, and intensity of rainfall events from March 30 to May 11 were similar to those of January 18 to February 21, but the pool response was not as great. This general decline in flow rate, pool level, and magnitude of pool response continued throughout May and June 1990. The more subdued response suggested that significant amounts of overburden had to become resaturated before pool recharge could occur. Only large, consistent rainfall periods such as the one of July 10 to 16 were capable of achieving the resaturation necessary to permit substantial pool recharge during the summer months.

Water Quality Considerations

Mine Discharge. Water quality was monitored weekly at the mine discharge throughout the study period, and water quality in the voids and pillars was monitored periodically. In general, the concentrations of contaminants at the discharge showed only minor variations over time. The concentration of acidity at the discharge is plotted along with the discharge flow in Figure 10; all other contaminant concentrations, such as iron, sulfate, and manganese, behaved in a similar manner. From April through June 1990, acidity concentrations were somewhat lower than at other times of the year. However, Figure 11 shows a very strong linear relationship between acidity loading (flow times concentration) and discharge flow.

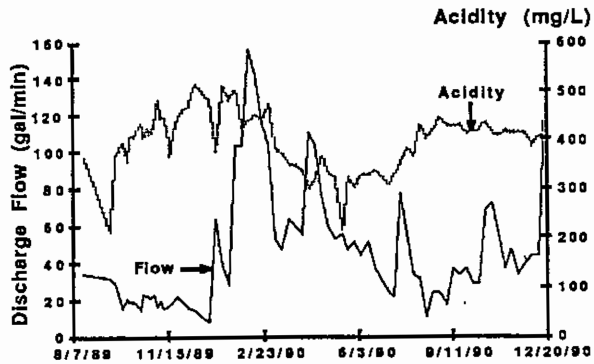

Figure 10. Acidity concentrations and discharge flows, Keystone site.

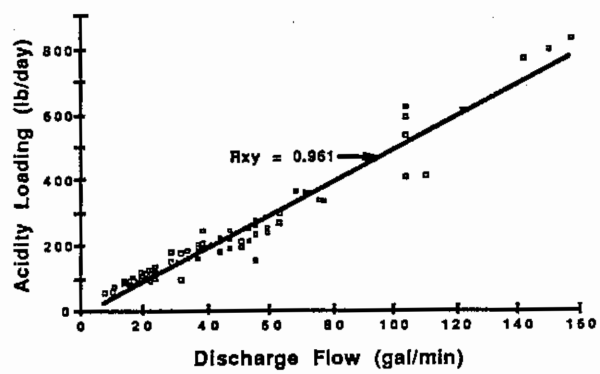

Figure 11. Linear regression - acidity loading vs. discharge flow rate, Keystone site.

This suggests contaminant loading rates were governed by flow variations, with concentration differences playing only a minor role; this is the case for most deep mine discharges. The slightly reduced concentrations during April through June may reflect the delayed release of water that had been diluted by infiltration and stored in upper reaches of the mine pool during the high-recharge period between January and March. The consistency of acidity concentrations throughout the observation period suggested that the overall rate of acid production and/or salt dissolution in the pool system was relatively constant.

Voids vs. Pillars. Figure 12 compares the average values of six major acid mine drainage parameters (pH, acidity, total iron, sulfate, aluminum, and manganese) for the mine void wells, the pillar wells, the vent hole, and the mine discharge. The differences in contaminant concentrations among the five void wells were minor, so they were averaged for comparison in Figure 12; the same was true for three of the four pillar wells (5, 7, and 9).

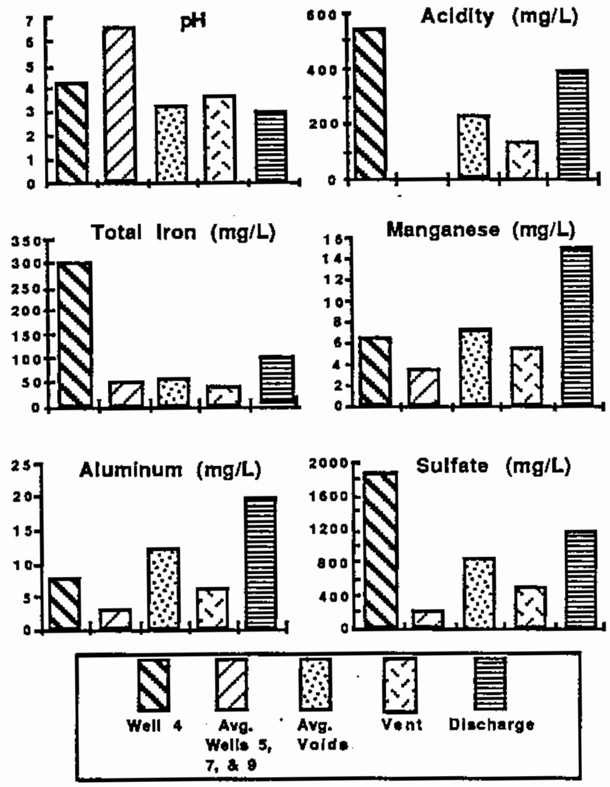

Figure 12. Comparison of water quality in mine voids, pillars and discharge, Keystone site.

The significant differences in water quality between the pillars and voids supported the assumptions that lateral flow occurred mainly through the voids, and that the pillars were recharged from above rather than from the side. For example, the water quality in wells 5, 7, and 9 was generally better than in the voids; conversely, the water quality in well 4 was substantially worse. If large amounts of lateral flow were occurring through the pillars, greater overall similarity in water quality would be expected. Note in Figure 12 that the water quality in the vent hole, which is open only to the overburden, was generally better than in the voids but poorer than in wells 5, 7, and 9. This was not inconsistent with the assumption of pillar recharge by vertical flow; the water quality differences could indicate either inherent spatial variations in acid production within the overburden or changes in water quality after downward flow into the voids or pillars.

In this regard, the extremely poor water quality of well 4 was quite anomalous. Acidity, total iron and sulfate concentrations in well 4 were consistently higher than either the voids or the discharge, while pH was higher and aluminum and manganese concentrations were lower.

Clearly, acid mine drainage existed at well 4, but the source of the acidity cannot be accurately identified. For reasons described above, lateral flow from an adjacent contaminated entry was considered to be unlikely. One possibility is that a localized zone of pyritic overburden or coal exists at well 4. Further research to investigate the cause of the poor water quality at well 4 was beyond the scope of this study.

__Voids vs. Discharge.__ Figure 12 also shows that water quality in the voids, while indicative of acid mine drainage, was generally better than water quality at the discharge. One possible explanation for these differences is that a zone of acid-producing material, either within the mine or the overburden, may be located between the wells and the discharge. The former possibility was considered because, at the time when the mine was operating, it was not uncommon for mine operators to dispose of acid-producing refuse material in unused entries near the portal area. Overall contaminant concentrations would increase as water from the wellfield flowed past this area. It was also noted that the mean percentage of ferrous iron in the voids was somewhat higher than at the discharge (86 vs. 75 %). Under the scenario above, this difference may have occurred due to conditions within the discharge borehole and the 135 ft length of PVC pipe that connected the borehole to the discharge sampling point. Here, the turbulent flow conditions and exposure to the atmosphere would allow oxidation of some of the iron from the ferrous to the ferric state.

A second, more likely reason for the differences in water quality between the voids and the discharge was that flow from other, unmonitored entries contributed greatly to the total discharge flow. Examination of the mine maps (see Figures 3, 4, and 5) showed that the discharge borehole was located at the intersection of one of the main mine entries and an apparently isolated set of entries that had been driven to the southwest. If the latter were indeed isolated from the rest of the mine openings, flow through them would be insignificant compared to flow through the monitored main entries. However, if an open connection between these entries and the rest of the mine were present, and the monitored entries were partially blocked in some manner (e.g., by dumped refuse or buildup of iron hydroxide precipitates) a large percentage of the total pool flow could bypass the wellfield. The discharge water quality would thus reflect, to a significant extent, the quality of the water flowing through the unmonitored entries.

__Water Quality Stratification.__ If the second flow scenario described above were true, flow through all entries would not be uniform as previously assumed, and the flow velocity through the monitored mine entries would be close to zero. Under such near-stagnant conditions, a marked worsening of mine water quality with depth has been noted (Ladwig et al 1984). In order to check for such water-quality stratification, an interval sampler was used to collect water samples from the top, center, and bottom of the voids, which were each approximately 6 ft in total height. Samples from all voids were grouped by level and statistically analyzed to check for water quality differences between levels. As shown in Figure 13, the water quality at the top of the voids was significantly better than at the center or bottom. Although the water quality at the center appeared to be somewhat better than at the bottom, the overlap of the confidence intervals prevented a definitive conclusion. These data suggested that some degree of stratification was occurring within the monitored voids, and that the flow velocity was relatively slow. It was decided that further experimentation would be necessary to define the flow rate through these entries, which would ultimately determine their suitability for alkaline injection.

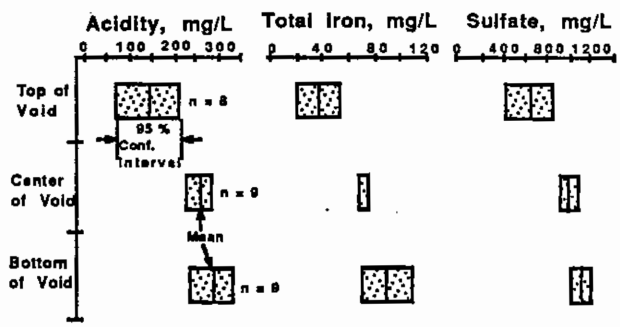

Figure 13. Stratification of water quality in mine voids, Keystone site.

__Tracer Test__

The approximate flow velocity within the mine pool can be estimated by introducing a chemical tracer into a monitoring well, noting the time of peak tracer concentration at the discharge, and dividing this mean travel time into the travel distance as measured on the mine map. Well 3 was chosen for the tracer test because it was located in an entry that was directly connected to the vast majority of upgradient voids, and was closer to the beach area than any other well of this type. Figure 14 shows the anticipated flow path from well 3 to the borehole discharge.

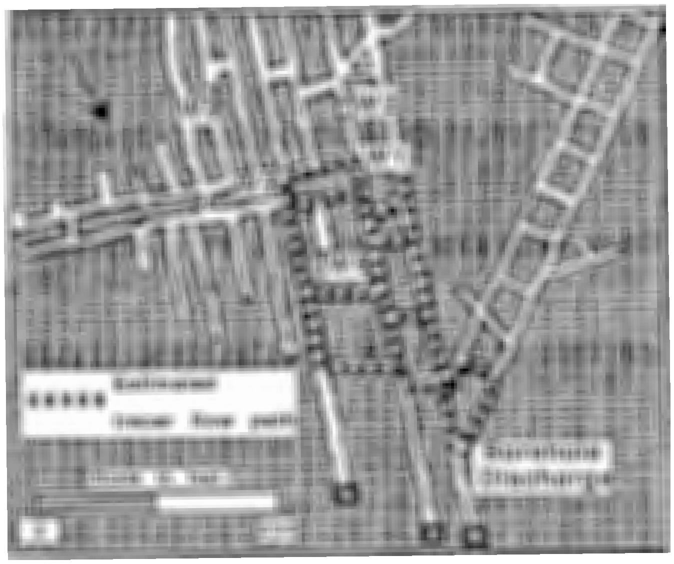

Figure 14. Estimated flow path of bromide tracer, Keystone site.

Bromide, in the form of a sodium bromide solution, was used as the tracer chemical. Bromide appeared to be an appropriate tracer choice because it is conservative, stable, and inexpensive (Davis et al 1985). Bromide concentrations as low as 0.1 mg/L could be detected by Bureau of Mines' analytical laboratory, and background concentrations of bromide were negligible. The quantity of tracer to be introduced was chosen such that if it were dispersed uniformly throughout all the entries in the assumed flow path, the bromide concentration at the discharge would be 15 mg/L, more than two orders of magnitude above the laboratory detection limit. The tracer test was initiated on February 14, 1990; 6.0 kg of granular sodium bromide were dissolved in water on the surface and introduced into well 3. An additional 30 gallons of fresh water were then added in order to flush the bromide from the well casing. Mine discharge samples were collected at 6-hr intervals by an automatic sequential sampler for a period of six weeks. Since no bromide was detected during this time, the sampling frequency was gradually reduced to once per day for the next eight months. Samples from wells 1, 3, and 6 were collected weekly to monitor tracer movement through the mine pool.

Early results of the tracer test suggested that flow was not uniform through all open entries. After 92 days of sampling, no trace of bromide was detected at the discharge or at wells 1 or 6, which were on the assumed flow path from well 3 to the discharge. During this time, the mean discharge flow rate was 76 gal/min, or 14,644 ft^3/day; under the uniform flow assumption, the flow velocity in the vicinity of well 3 would have been approximately 25 ft/day. Under these circumstances, traces of bromide would be expected in well 1 after 4 days, well 6 after 10 days, and at the discharge after 22 days. Obviously, flow was not occurring uniformly through all open entries as first assumed. However, bromide was apparently migrating of away from well 3, indicating that water in that entry was not completely stationary. Immediately after tracer introduction and flushing, a sample taken at the center of the void at well 3 contained 468 mg/L of bromide; after 92 days, the concentration had declined to less than 1.0 mg/L (see Figure 15). This decline could not be attributed to molecular diffusion because the initial bromide concentration was too dilute to produce significant solute movement via diffusion (Lide, 1990). Therefore, it was concluded that some flow, albeit slow, was occurring in the entry penetrated by well 3.

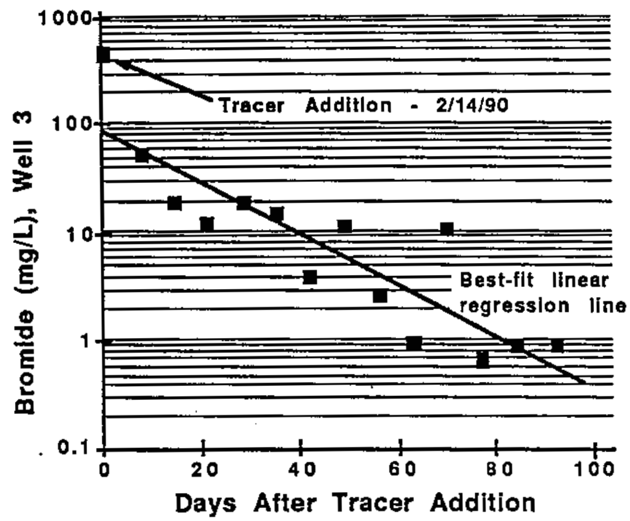

Figure 15. Dilution of bromide tracer in well 3, Keystone site.

In order to obtain a rough estimate of the velocity in the well 3 entry from the tracer data, a borehole dilution equation (Drost, et al, 1968; Grisak, et al 1977) was employed:

$$v_a = -(V/At) * \ln(C/C_o) \qquad (1)$$

where: v_a = apparent velocity
V = dilution volume
A = cross-sectional area of flow
t = time since tracer introduction
C = tracer concentration at time t
C_o = tracer concentration at t = 0

Support for using equation 1 to describe tracer movement is provided by noting that the plot of tracer concentration versus time on a semilogarithmic scale (Figure 15) approximates a straight line, as would be expected by rearranging the equation:

$$\ln(C) = -(v_a A/V) * t + \ln(C_0) \qquad (1a)$$

It was recognized that the use of equation 1 involved some error, partly from the underlying assumptions that flow is steady and that the tracer is homogeneously distributed throughout the dilution volume, and partly from the uncertainty associated with estimating the parameters, especially the dilution volume. In this case, the area was estimated at 108 ft^2, and the dilution volume was estimated by dividing the total tracer mass (6.0 kg) by the average tracer concentration at the center of the void over the time period being considered. Since the tracer was in an open conduit, the apparent velocity did not have to be corrected for wellbore and screen effects.

Velocities calculated from equation 1 during the first 3 months after tracer addition ranged from 1.9 to 4.5 ft/day, depending on the time frame being considered. Correlation was not found between the calculated velocity and measured mine pool elevation at a given time. At the mean calculated flow velocity, 2.8 ft/day, the tracer would have been expected at well 1 after 42 days and at well 6 after 70 days. The lack of tracer detection at these wells after 92 days suggested that the entries connecting well 3 to wells 1 and 6 did not constitute a primary flow path. Also, note that at a velocity of 2.8 ft/day, the tracer would be expected to arrive at the mine discharge after approximately 200 days. However, at this velocity and a cross-sectional flow area of 108 ft^2 at well 3, the mean discharge rate through that entry during the observation period would have been only 300 ft^3/day. This was only about 2 % of the mean mine discharge rate (14,644 ft^3/day) during the observation period. Since the remaining 98 % of the discharge flow would come from other sources in the mine, it was suspected that the bromide concentration would be diluted below detection limits by the time the tracer reached the discharge borehole. Therefore, no reliable quantitative estimates of travel time or flow velocity through the mine pool were obtained from the tracer test.

Alkaline Injection

Although a distinct flow path and travel time through the mine pool could not be identified, it was determined that a one-time attempt at alkaline injection would still be worthwhile. Even if no improvement in discharge water quality were achieved, monitoring of the water quality in the wells after alkaline injection would provide additional information about the mine pool hydrology. Based on an average discharge acidity of 402 mg/L, a minimum of 1570 kg of sodium hydroxide (NaOH) would be required to neutralize the estimated 4.6 million liters of water contained in all entries downgradient of well 3. On May 23, 1990, this quantity of NaOH (2000 gallons of 25 % sodium hydroxide solution) was injected into the mine pool. About half the solution was placed in well 3 to maximize the treated pool volume, and the other half was placed in well 6 with the intent of achieving a quicker response at the discharge. As with the bromide tracer, the wells were flushed with fresh water after injection to minimize the amount of alkaline reagent remaining in the well casings.

Results. A thorough discussion of the results of the alkaline injection treatment is provided elsewhere (Aljoe and Hawkins, 1991). Not unexpectedly, the treatment had no apparent effect on the water quality of the mine discharge. However, the water quality data obtained from wells 3 and 6 (Figure 16) provided further information about flow through the monitored entries.

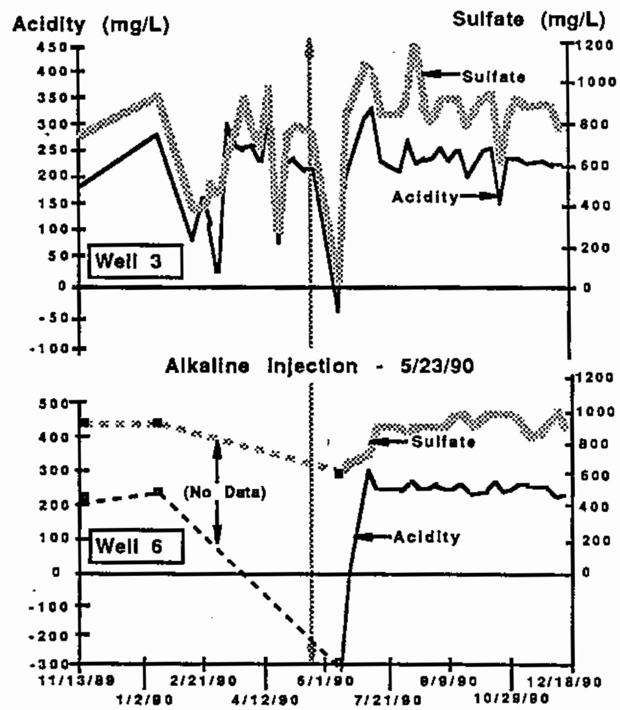

Figure 16. Acidity and sulfate changes in alkaline injection wells, Keystone site.

As expected, alkaline conditions (shown as negative acidity) were present in both wells immediately after injection; however, a concurrent decrease in sulfate concentration was also noted. Since sulfate concentrations typically remain constant during acid neutralization with sodium hydroxide, it is likely that displacement or dilution rather than neutralization was largely responsible for the decreased acidity. The return of the acidity and sulfate concentrations to their pre-injection levels after six weeks was interpreted as a movement of the displacing/diluting media (alkaline solution and flushing water) away from the injection wells. As with the tracer test, this result suggested that flow was occurring through the entries at wells 3 and 6, although not rapidly enough to comprise a substantial percentage of the total pool flow. Thus, the alkaline solution may have become mixed with such large volumes of untreated water that any neutralization effects have gone undetected. Also, much of the alkaline solution may have become trapped and stratified in a stagnant portion of the mine pool, and will remain unreacted unless flow velocities increase enough to promote more rapid mixing and downgradient movement. These possibilities could be examined by continuously injecting larger quantities of alkaline solution, but such an effort was beyond the scope of the current study.

Future Work

One of the primary efforts in the future will be to install up to four additional monitoring wells in the area shown in Figure 17. If open connections exist between this area and the remainder of the upgradient mine workings, wells in open entries could intercept a primary flow path. After these wells are installed and baseline water quality is established, tracer tests will be performed to determine pool flow velocity and travel time.

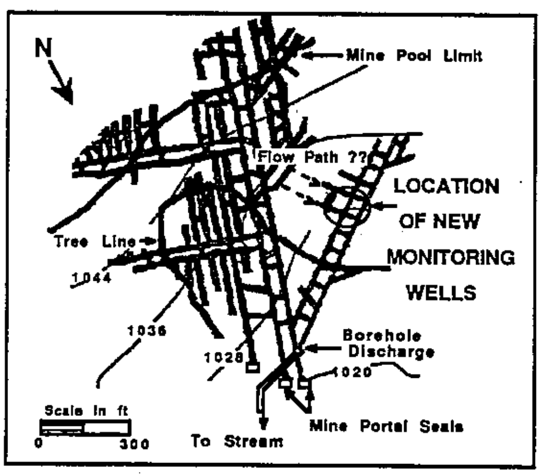

Figure 17. Proposed location of new wells, Keystone site.

Hydrologic Investigation - Friendship Hill National Historic Site

For several reasons, the hydrologic investigation at the Friendship Hill site (see Figures 1 and 18) was not as extensive as for the Keystone site. The mine map was not as complete or as detailed (e. g., no mine floor elevations), and the history of the mine and the circumstances under which the mine pool developed were more complex and not as well-documented. Early field reconnaissance revealed that the mine pool had at least two significant discharge points, which would have made a detailed investigation much more complex, costly, and time-consuming. Finally, several of the Friendship Hill mine pool monitoring wells were vandalized about six months into the investigation, thereby discouraging the use of this site for alkaline injection and reducing the near-term need to perform more rigorous studies. Nevertheless, the results of the preliminary investigation suggested that the nature and behavior of the mine pool were substantially different than those of the Keystone site.

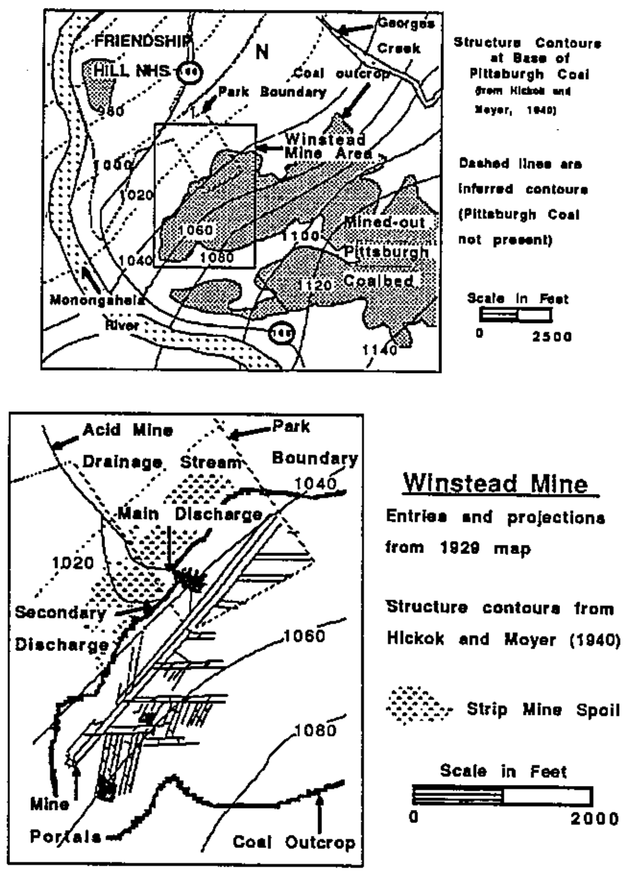

Figure 18. Geologic structure and mining activity in vicinity of Friendship Hill site.

Site Background

Figure 18 (from Hickok and Moyer, 1940) illustrates the general geologic structure in the vicinity of the Friendship Hill site (strike N 55° E, dip approx. 1.3° NW). Ground water flow in the study area is controlled by both topography and geologic structure; however, widespread mining in the area has made a significant impact on the ground water flow regime. A map prepared by Shaulis (1985) showed that all of the Pittsburgh coal seam areas shown in Figure 18 had been mined by underground methods, and strip mining had been performed on most of the Pittsburgh seam outcrop. The underground mines act as ground water sinks, and the associated low-permeability underclays result in numerous mine discharges along the Pittsburgh seam outcrop line. Because of the geologic structure, these effects are most prominent on northwest facing outcrops.

The abandoned mine at the Friendship Hill site was located in the Pittsburgh coal seam, and was operated by the Winstead Coal Co. in the 1920s and perhaps the 1930s. A mine map, dated 1929, showed the location of existing and projected mine entries with respect to coal outcrops, property lines, and an access road, but did not contain information on mine floor elevations or other topographic features. Property line boundaries and coal outcrop lines were correlated as closely as possible with current information to establish the position of the Winstead mine with respect to National Park Service property (Figure 18). There are actually two mapped mines at the site; the main mine discharge appears to originate from a partially-collapsed opening of a very small, unnamed mine that is surrounded by the larger Winstead mine. Mine maps suggested that as the main entries of the Winstead mine approached the small mine from the southwest, a single entry was driven almost due north, connecting the Winstead mine to the smaller mine. The location of this entry suggests that it served to drain water away from the Winstead mine and out through the smaller mine. Although the mapped portion of the Winstead mine stopped just to the east of the small mine, mine projections indicated that the Winstead mine continued its development to the north and east. Considering the relative locations of the mines and geologic structure, it is likely that the small mine continues to serve as a drain for much of the Winstead mine, as well as other mines to the southeast (upgradient) that may be interconnected with the Winstead mine.

Field observations were the only means of locating mine discharge points. Only one other discharge was found within 1000 ft of the main discharge; this secondary discharge, shown in Figure 18, actually represents the discharges from two mine openings located about 350 ft southwest of the main discharge and 100 ft from each other. One of these openings was relatively intact and contained an air-water interface that provided a visual indicator of the mine pool level. Access for water sampling and flow measurement was precluded by pooled water in front of this opening. The second mine opening was completely collapsed, but its discharge contained a freely-flowing section from which representative water samples were taken. The two discharges combined on the surface within 10 ft of the second opening, and flow was measured with a portable flume at this point.

Much of the barrier coal between the Winstead mine and the northwest coal outcrop, and perhaps some of the pillars within the Winstead mine and the unnamed mine, were subsequently removed by strip mining. Field observations confirmed the presence of strip mine spoil piles to the northwest of the existing coal outcrop. However, the extent of strip mining with respect to the underground mines could not be determined with enough accuracy to permit mapping. Field observations also revealed the existence of several large sinkholes above the mine that were obviously the result of mine subsidence. However, the sinkholes could not be related to specific mine areas, and the general extent of caved conditions in the mine could not be determined prior to drilling of monitoring wells.

Monitoring Wells. If the pool surface were horizontal as at the Keystone site, the difference between the elevations of the pool and the seat clay (pool depth) would decrease to the southeast. The drilling plan was to first complete several holes within 200 ft southeast of the main discharge, where a mine pool was almost certain to be present. These holes would ensure that hydrologic monitoring and tracer tests could be conducted if subsequent holes farther away from the discharge failed to intercept the pool. Drilling would then proceed to the southeast until a beach area was reached or until ten holes were drilled. Well construction was to be the same as at the Keystone site.

Figure 19 shows the locations of all monitoring wells with respect to surface topography, the mine discharges, and the site access road. The first three wells all penetrated a highly rubblized zone or zones, consisting of numerous small (1 to 3-in) voids near the mine level. Cuttings from the air rotary drill were lost after the first small void was encountered, thereby eliminating the use of cuttings to identify the location of the seat clay. The driller's "feel" for resistance to penetration provided only a rough estimate of the depth to clay. Therefore, the rest of the drilling was not conducted as planned because the pool height could not be determined accurately. The fourth through ninth wells were drilled to the east and southeast, in locations that provided relatively easy access for the drilling rig and at least 75 ft spacing between wells. Wells 4 through 8 encountered caved conditions similar to the first three; this result, coupled with the observations of surface subsidence (Figure 19), indicated that the mine entries were mostly caved in the area accessible to drilling. Well 9, located only 50 ft from the southeast park boundary, penetrated solid coal. The pool depth at well 9 was found to be more than 7 ft; this suggested that the mine pool actually extended beyond park boundaries to the southeast.

Well 10 was drilled toward the southwest corner of park property, and encountered a 9 ft high void. However, rapid hole collapse prevented the installation of casing to the full hole depth; the bottom of the casing was approximately 3 ft above the seat clay. Extrapolation of water levels in the other wells indicated that the pool elevation at well 10 would have been slightly below this. Indeed, no water was detected in well 10, so the mine pool, if present, was no more than 3 ft above the seat clay at this point. Experience of mine operators in this area has shown that the Pittsburgh coal seam contains numerous localized "rolls" that oppose the general structural trend. Well 10 may have been drilled into an entry located on a high spot in the local structure; this would account for the shallow (less than 3 ft) pool depth.

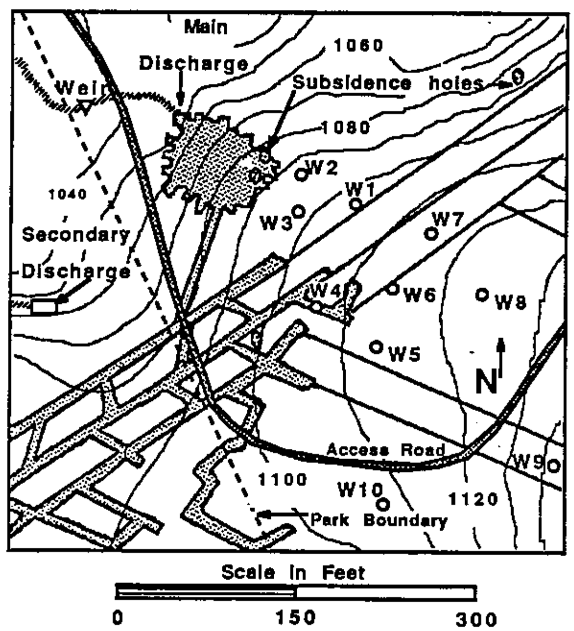

Figure 19. Surface features and topgraphic contours, Friendship Hill site.

Mine Pool Hydrology

As with the Keystone site, the first task after completion of well drilling at Friendship Hill was to characterize the nature of the subsurface flow system. Unlike Keystone, however, the piezometric surface at Friendship Hill was not horizontal, but had a distinct, regular hydraulic gradient (Figure 20); Figure 21 is a cross-section through the wellfield at the Friendship Hill site.

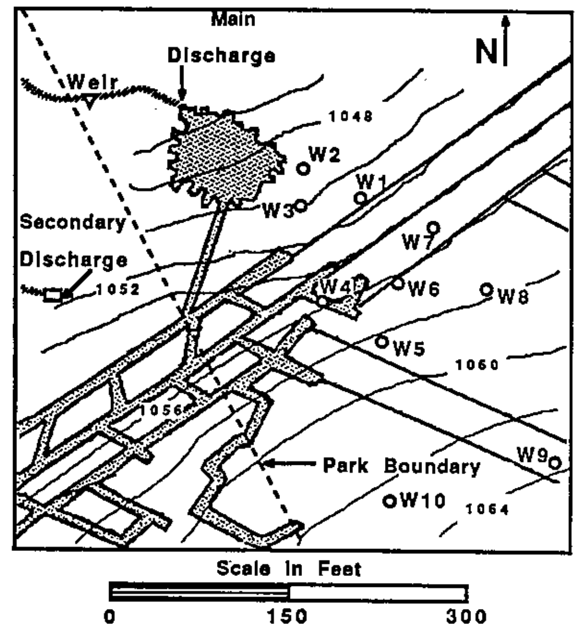

Figure 20. Mine pool level contours, Friendship Hill site.

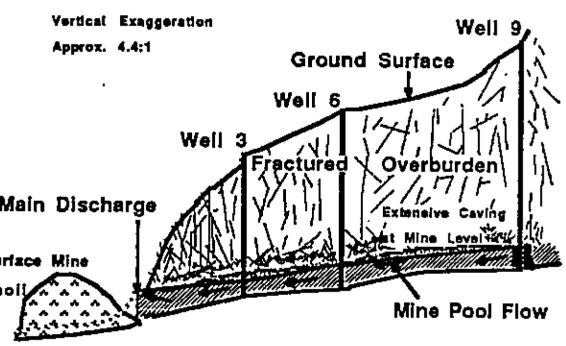

Figure 21. Cross-section through wellfield at Friendship Hill site.

Because of the water surface gradient, the flow system in the wellfield at Friendship Hill was more like that of a water table aquifer than that of a reservoir with an underdrain. However, this water table is quite different than it would have been had mining not occurred. In unmined conditions, the water table would have roughly paralleled the surface topography and existed in a series of perched aquifers. After mining, the increase in vertical ground water flow resulting from widened overburden fractures and mine pumpage probably desaturated the overburden. Even after mine pumpage ceased and the deep strata collapsed into the mine openings, the overall porosity and permeability of the caved zone would still have been much greater than that of the fractured overburden. Although the caved material appears to have provided enough resistance to flow to allow the development of a water table gradient, its capability to store water and transmit it to the free drain (mine opening) at the low point of the flow system appears to have been great enough to suppress the redevelopment of the pre-mining water table. Thus, the current flow system may represent an equilibrium condition between high recharge to an aquifer of high transmissivity and storativity (the caved material) and discharge from a free drain at its base.

One factor complicating the flow system through the wellfield is the inherent heterogeneity of the aquifer formed by the caved material. The caving process does not occur uniformly, and some entries or portions of entries that were better supported than others would remain partially open to serve as preferred flow paths. This was evident in preliminary aquifer tests (slug withdrawal) that were conducted in four of the wells. In wells 6 and 7, water level recoveries occurred so rapidly that conventional analytical methods were not appropriate. In wells 4 and 8, recovery occurred as expected; hydraulic conductivities calculated by the Bouwer and Rice (1976) method were 3.9×10^{-5} ft/min and 2.6×10^{-3} ft/min, respectively, which was not unexpected for this material. The vast differences in well responses were similar to those observed by Hawkins and Aljoe (1991) in heterogeneous surface mine spoil, and supported the notion that preferred flow paths through the caved material could exist despite the presence of a regular steady-state water table.

Perhaps the most important aspect of the mine pool flow system is the likelihood that not all of the flow at the main and secondary discharges comes from the monitored area. The drainage entry connecting the Winstead mine to the smaller mine (see Figure 18) probably continues to contribute a substantial but unquantifiable percentage of the main discharge flow. A similar uncertainty exists for the secondary discharge. Given the location of these openings with respect to the rest of the mine and geologic structure (see figs. 18-20), the hydrologic connection, if any, between the wellfield and the secondary discharge is even less clear. Therefore, interpretations of hydrologic and water quality data collected at the site must reflect this uncertainty.

<u>Mine Discharge Flow Rates.</u> Flow rates of the main mine discharge were measured at least once per week from late October 1989 through early November 1990. During the study period, the measured flow rates ranged from 24.5 to 193 gal/min, with a mean and median of 65 and a standard deviation of 31 gal/min. Unlike the Keystone site, extremely low flows (less than 20 gal/min) were not measured at the Friendship Hill site. One possible reason is that the Friendship Hill pool area is much larger, allowing higher flows to be sustained for longer periods with a minimal drop in pool level.

A key factor governing the discharge flow rates of the mine pool at Friendship Hill was the existence of the known secondary discharge, and perhaps other discharge points that were not found during field reconnaissance. Figure 22 shows the flow rates of the two measured discharges over the five-month period when secondary discharge flow rates were measured. The strong positive correlation between the flow rates at the main and secondary discharges (Figure 23) supported the assumption that the two were connected to the same mine pool.

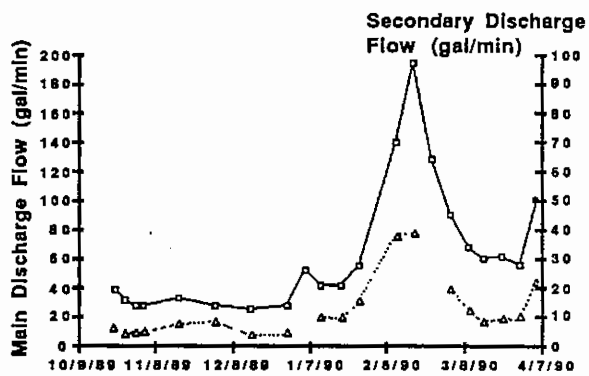

Figure 22. Flow rates of main and secondary discharges, Friendship Hill site.

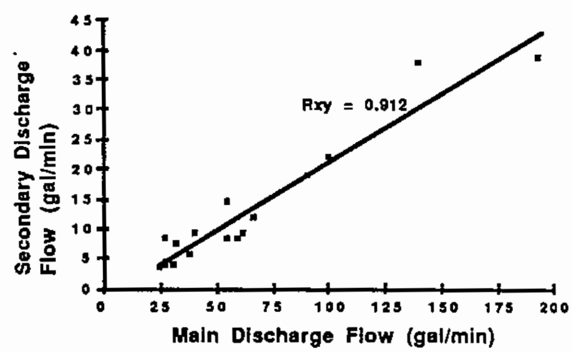

Figure 23. Linear regression - flow rates at main vs. secondary discharge, Friendship Hill site.

Note in Figures 19 and 20 that the topographic and water surface elevations of the secondary discharge are higher than those of the main discharge. Therefore, it is possible that the secondary discharge functions as a type of relief valve for the mine pool, especially since one of the mine openings at this discharge appeared to be unrestricted. The effect of the secondary discharge, along with other unmonitored discharges, would be to reduce the flow rate of the main discharge, especially during high-flow periods.

If the secondary discharge were a preferred outlet for the mine pool during high recharge periods, it would be expected that the percentage contribution of the secondary discharge to the total discharge (secondary plus main) would increase with total discharge. A slight positive correlation between these two variables was found (R_{xy}= 0.295), but the greatest percentage contribution of the secondary discharge did not occur when the measured flows were highest. The lack of a strong correlation may be related to the small size of the data set (19 samples) and the inaccuracy of flow measurements made with the portable flume at the secondary discharge. However, it is possible that other upgradient mine openings limit the maximum flow of the secondary discharge and reduce its contribution to the total pool flow.

Mine Pool Levels. Water levels in all nine water-bearing monitoring wells were measured weekly from November 1989 through March 1990. After three of the wells were vandalized beyond repair in early April 1990, monitoring frequency was gradually decreased to twice monthly, but continued until early November 1990. The most notable finding was that the water levels in all wells remained almost the same throughout the study period despite the wide variations in discharge flow (Figure 24).

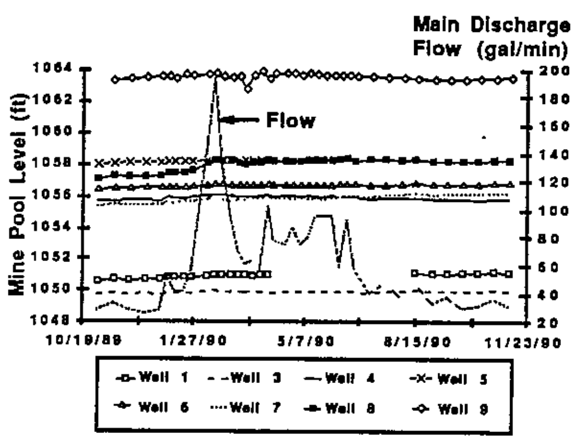

Figure 24. Water levels in monitoring wells, Friendship Hill site.

This contrasted markedly from the Keystone site, where pool level fluctuations were small but easily detected. Of course, in order for flow changes to occur, the mine pool level at Friendship Hill would have had to change, but the large size and storage capacity of the pool and the presence of multiple discharge points may have rendered the changes undetectable. For example, preliminary estimates of total pool storage capacity indicated that net pool discharge (total discharge minus recharge over the same time period) would have to be about 1.5 million gallons in order for the pool level to drop 0.25 inches, the functional accuracy of the electric water level measurement tool. Noting that the two Friendship Hill discharges release about 30 gal/min at low flow, and assuming that they represent about 20 % of the total flow from all discharges, approximately 7 days of zero recharge would be required for a detectable drop in pool level to occur. Considering the ease of pool recharge through the fractured overburden and the lack of long dry spells during the study period, actual pool drops would have been difficult to detect. Similarly, even the highest pool recharge rates would not result in detectable pool rises because such recharge could be dissipated almost instantaneously by high flows at multiple discharges, at least some of which have no restrictions to flow.

Response to Precipitation. Daily rainfall data at Friendship Hill were collected and recorded by National Park Service personnel. Figure 25 shows that the flow rate of main mine discharge responded to precipitation in a manner similar to the mine discharge at the Keystone site (Figure 9), for reasons previously discussed. During the late summer and fall, large precipitation inputs produced minimal changes in discharge flow rates. Conversely, following the first major snowmelt of the season and continuing through spring, even minor precipitation

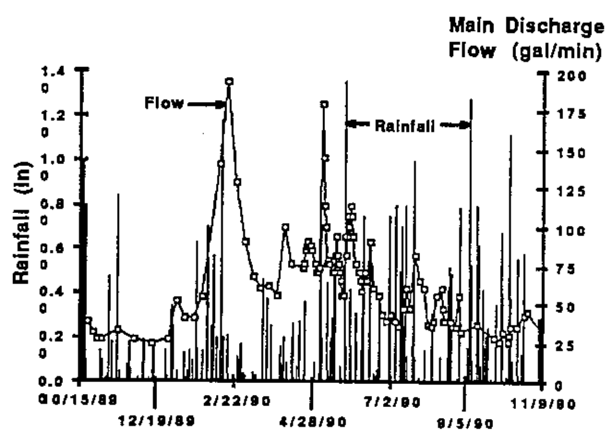

Figure 25. Response of Friendship Hill mine pool to rainfall, October 1989 to November 1990.

events produced very rapid increases in flow. Allowing for these seasonal effects, the magnitude of the flow response generally reflected the intensity and duration of the antecedent precipitation. At Friendship Hill, as at Keystone, it is likely that the relationship between main discharge flow and precipitation is controlled by greater pool recharge rates during the winter and spring months. However, for reasons discussed above, this could not be confirmed by examining the mine pool water levels.

Water Quality Considerations

Mine Discharge Water Quality. Water quality samples were collected from the main and secondary discharges each time a flow measurement was made. As with most deep mine discharges, contaminant loading rates in both locations were dominated by flow. Plots of contaminant loadings versus flow at Friendship Hill were similar in appearance to those at Keystone (see Figure 12), indicating that variations in contaminant concentrations were small compared to variations in flow. However, contaminant concentrations appeared to change slightly with flow variations. Figure 26 shows that from October 1989 through June 1990, contaminant concentrations at the main discharge (represented by acidity and sulfate) dropped noticeably during periods of increasing flow, and rose as the flow rate declined. This pattern suggested that some dilution of the mine drainage was occurring during periods of increased flow. The source of this dilution could not be confirmed; it may have resulted from general recharge throughout the mine pool, locally enhanced infiltration through the heavily-fractured overburden just behind the main discharge (see Figure 21), and perhaps small amounts of surface runoff into the weir where water samples were collected.

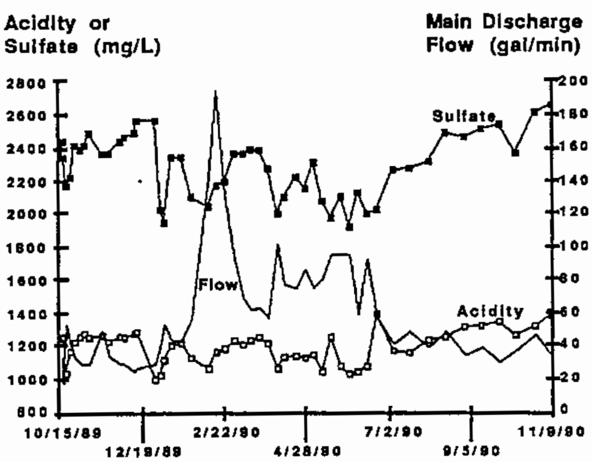

Figure 26. Acidity and sulfate concentrations, main discharge, Friendship Hill site.

Note also in Figure 26 that contaminant concentrations increased steadily during July through November 1990, and that the correspondence between contaminant concentration decreases and flow increases was less pronounced. Despite reduced infiltration during this period, the unsaturated caved zone and fractures immediately above the mine pool would still contain enough moisture to sustain pyrite oxidation and acid salt formation. When pool recharge became sufficient to produce a flow increase, the effects of dilution may have been offset by increased salt dissolution by infiltrating waters. Due to the lower frequency of such flushing events during the summer, fresh pyritic surfaces exposed as the result of salt dissolution would have more time to react before the next event. The increasing contaminant concentrations and decreasing flows shown in Figure 26 may represent the net result of the lower frequency and magnitude of flushing events.

Figure 27 shows that the percentage of ferrous iron in the main discharge was never greater than 30 %, and was consistently below 5 % during the high-flow period from January through June 1990. This differs markedly from the Keystone site, where the iron in the discharge was consistently greater than 75 % ferrous. The lower ferrous percentages at Friendship hill probably occurred because the mine pool had much greater access to oxygen than the pool at Keystone, thereby enhancing oxidation of iron from the ferrous to ferric state by direct aeration and the action of aerobic bacteria. The numerous subsidence sinkholes and associated overburden fractures at Friendship Hill, which were absent at Keystone, allowed easier diffusion of atmospheric oxygen. Also, the pool surface at Friendship Hill was located below the top of the mine void (or caved zone) throughout the site, whereas the Keystone pool surface was well above the void except

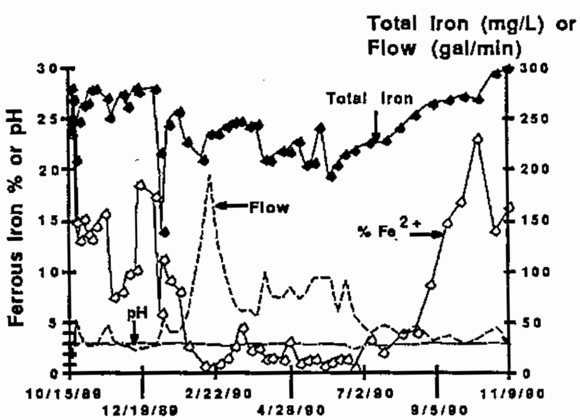

Figure 27. Concentrations of total iron, ferrous iron, and pH, main discharge, Friendship Hill site.

in the beach area (compare Figures 6 and 23). Thus, the pool surface area open to oxygen and subsequent ferrous to ferric conversion was much greater at Friendship Hill. The pH of the main discharge remained nearly constant (between 2.5 and 3.0) throughout the study period, suggesting that bacterially-mediated iron oxidation was dominant. Also note in Figure 27 that the ferrous percentage appeared to be inversely related to flow. This behavior may be related to the greater flushing of ferric salts from pyritic surfaces near the air-water interface during high-flow periods. The concentrations of all acid mine drainage contaminants were consistently higher at the secondary discharge than at the main discharge. However, the same relationships between concentration, flow, ferrous percentage, and pH discussed above (Figures 27 and 28) were also found at the secondary discharge. This supported the assumption that both discharges drained the same large pool, but suggested that significant water quality differences may have been present in different areas of the pool.

<u>Monitoring Well Water Quality.</u> A regular, comprehensive well sampling program was not conducted at Friendship Hill, primarily because it became clear that the Keystone site was more suitable for alkaline injection. As shown in Figure 28, the water quality in the eight wells that were completed in caved material varied widely; note the wide confidence intervals (95 % level) around the mean. This suggested that although all areas of the pool produced acid mine drainage, some locations were more active than others. For example, the worst individual sample (well 5, March 15, 1990) contained an acidity concentration of 7393 mg/L, total iron of 2032 mg/L, and sulfate of 8775 mg/L. This variability, if indicative of conditions in the entire pool, could be responsible for the observed water quality differences between the main and secondary discharges. In general, the water quality in the wells was much poorer than at the discharge. However, contaminant concentrations in well 6 were closer to those of the main and secondary discharges than most of the other wells (Figure 28), and showed the same behavior over time as the main discharge (see Figure 26). Ferrous iron percentages in well 6 were relatively low (1 to 40 %), but were consistently higher than at the main discharge and showed the same steady increase from July through October 1990 (see Figure 27). This was consistent with the previous evidence of less pool dilution and less ferric salt flushing during the low-recharge periods of late summer and early fall.

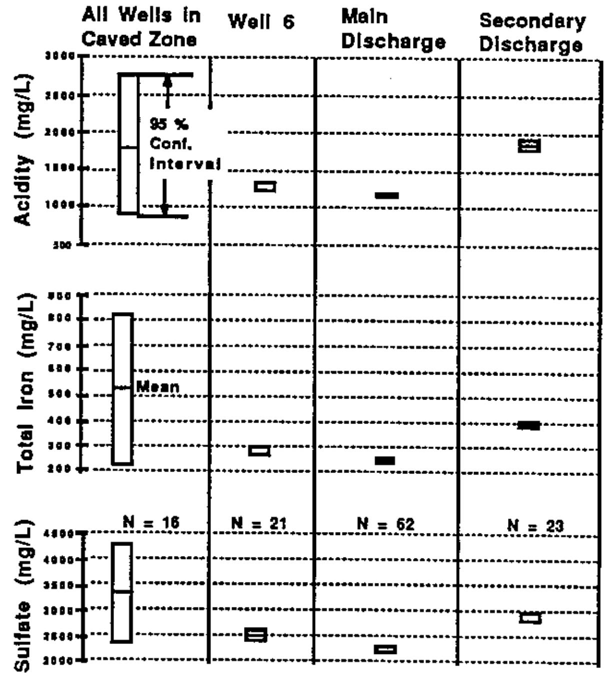

Figure 28. Comparison of water quality in monitoring wells and discharges, Friendship Hill site.

<u>Tracer Test</u>

It was determined that a bromide tracer test similar to the one at Keystone could be conducted at Friendship Hill despite the vandalism and reduced sampling schedule. Well 6 was chosen for tracer introduction because it was hydrologically upgradient and within 100 ft of two of the remaining accessible monitoring wells 4 and 7). Also, its water level had recovered almost instantaneously after slug withdrawal, suggesting that it may have intercepted a preferred flow path in the caved zone, and its water quality was similar to that of the main discharge. Because of the large size of the overall pool and porous-medium characteristics of the pool flow system in the wellfield, flow velocities were expected to be relatively slow. For example, if it were assumed that: (1) flow occurred entirely by porous-media methods; (2) the hydraulic conductivity of the medium equaled the average of the measured conductivities in wells 4 and 8 (3.02×10^{-4} ft/min); and (3) the porosity of the medium were 60 %, then application of Darcy's law would yield a travel time of 42 years between well 6 and the main discharge. Tracer detection at the main discharge therefore depended on the existence of a preferred flow path from well 6.

The tracer test began on April 20, 1990, with the introduction of approximately 6 kg of sodium bromide in solution form, followed by approximately 30 gallons of flushing water. If this quantity of sodium bromide were uniformly dispersed throughout the pool volume downgradient of well 6 (estimated at approximately 4 million gallons), the concentration at the main discharge would have been only 0.4 mg/L, barely above the detection limit of the laboratory equipment. However, if a preferred flow path did exist, as required for detection within a reasonable time period, uniform dispersion would not occur and the concentrations reaching the discharge would be higher. Weekly sampling of the downgradient wells and daily sampling of the main discharge was believed to be sufficient to detect tracer arrival and subsequent movement. The secondary discharge was not monitored for tracer because it was farther from well 6 and its potential hydrologic connection with the wellfield was not demonstrated.

Six months after the start of the tracer test, no evidence of bromide had been detected at the main discharge. Given the large pool size and the amount of tracer added, this was not unexpected. However, Figure 29 summarizes the somewhat surprising results of the well sampling conducted during the tracer test. Within one week after tracer addition in well 6, the bromide concentration in well 4 had increased to 21.5 mg/L; it then decreased steadily to below the detection limit (0.1 mg/L) six weeks after tracer injection. This suggested the peak tracer concentration in well 4 had occurred before the first sample was taken, and that the mean travel time between wells 6 and 4 was less than one week. Although the decline in bromide concentration over time in well 6 was much more erratic than in well 4, the rate of decline was similar in both wells. The straight lines on the semilogarithmic plot of Figure 29 suggest that flow-related dilution was occurring. Since the distance from well 6 to well 4 was approximately 100 ft, the flow velocity would have been more than 14 ft/day, considerably higher than expected. Although the projected locations of wells 6 and 4 on the mine map (see figs. 19 and 20) suggested that an open mine entry may have connected the two, well 4 was one of the wells that responded in a steady, predictable manner in the slug withdrawal tests, with a relatively low hydraulic conductivity of 3.9×10^{-4} ft/min. Thus, the rapid flow velocity suggested by the tracer test could not be directly attributed to the presence of an open conduit between wells 6 and 4. However, since a slug test influences only a very small aquifer volume, there may have been a conduit in the vicinity of wells 6 and 4 that was not detected in the slug tests.

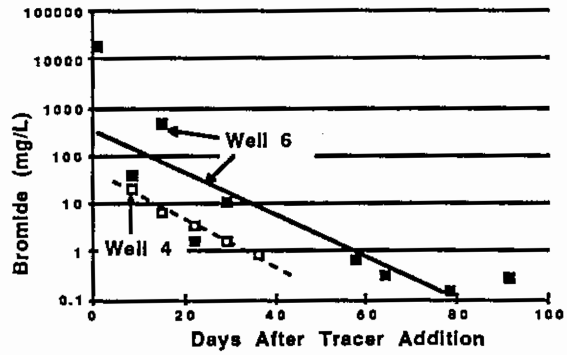

Figure 29. Results of bromide tracer tests, Friendship Hill site.

Future Work

A complete understanding of the mine pool hydrology at the Friendship Hill site can be obtained only by broadening the study to include all mine discharges that occur along the section of Pittsburgh coal outcrop shown in Figure 18. Monitoring wells should be installed in the mined areas near several of the discharges, and the hydrologic and water quality data should be collected over a period of several water years. In this manner, the observed hydrologic conditions at Friendship Hill (e.g., stable pool levels, regular water table gradient in caved zone) can be placed in the proper regional perspective and related to behavior at sites which may drain the same large mine pool.

Summary and Discussion

The hydrologic studies conducted at the Keystone and Friendship Hill sites in western Pennsylvania showed that abandoned underground mine pools can have substantially different flow systems. At the Keystone site, the flow system was relatively simple, primarily because a single mine with a single major discharge point was involved. The mine pool formed behind portal seals that were deliberately placed to cause the mine to flood. The mine entries appeared to be mostly intact, with minimal pillar removal, thereby providing a set of highly transmissive flow paths at the base of the mine pool. The net result was a horizontal piezometric surface that was above the top of the mine void in all locations except for a "beach area" at the upgradient extremity of the pool. Flow within the pool was assumed to consist of downward flow through the saturated overburden to the mine voids, and lateral flow through the voids to the discharge. Flow direction within the voids was assumed to be parallel to the structural gradient of the mine. Fluctuations in pool level, although small, were easily observed and could be directly related to precipitation events and changes in discharge flow. This implied a relatively small pool area available for storage. A tracer test and subsequent injection of an alkaline solution into mine pool monitoring wells revealed that flow rates through the monitored entries, although detectable, were relatively slow. This indicated that the monitored entries may not be carrying the major portion of the pool flow. Mine maps were used to identify other entries that were capable of carrying significant pool flow to the discharge point, consistent with the conceptual flow system.

The Friendship Hill site was significantly more complex than the Keystone site, both in mining history and current hydrologic behavior. Numerous mines, both large and small, penetrated the coal seam at different elevations along a sinuous outcrop line. Some or all of these mines were probably interconnected, allowing flow to occur freely over a large mined area. The resulting pool or pools contains many discharge points, each at a different elevation. Subsequent strip mining of the outcrop probably exposed additional mine openings and created new discharge points. Portal seals were not emplaced at the monitored discharges; although collapse of strata at the discharge openings and strip mine spoils that were pushed into these openings have provided a damming effect, a significant zone of saturated overburden behind the discharges did not develop. Water levels in monitoring wells revealed a regular water table gradient in an area of predominantly collapsed entries behind a major discharge point. However, not enough data were available to determine either the proportion of the total discharge flow coming from the caved zone or the proportion of the mine that may be governed by the implied porous-media flow system. In marked contrast to the Keystone site, wide variations in flow were not accompanied by detectable changes in pool level; in fact, water levels in all wells remained almost constant throughout the one-year study. A reasonable explanation for this behavior is that the pool storage area is so large that extremely long periods of zero pool recharge would be required to cause detectable decreases in pool elevation. Conversely, increases in pool elevation during periods of high recharge are prevented by the existence of multiple pool discharge points, some of which provide minimal resistance to flow. A tracer test revealed a strong hydrologic connection between the tracer injection well and one downgradient well in the caved material, but the tracer was not detected at the main discharge six months after injection. This result, along with preliminary aquifer testing, suggests that the caved material is highly heterogeneous. This "aquifer" may behave as a porous medium in terms of steady-state water levels, but flow may occur primarily through discrete channels under transient recharge conditions, as observed in surface mine spoils (Hawkins and Aljoe, 1990)

The implications of the studies described in this paper are somewhat problematic in terms of the future of in-situ neutralization of pooled water in abandoned underground mines. The unsuccessful initial alkaline injection at the Keystone site, where comparatively good information was available prior to the hydrologic study, exemplifies the difficulty in obtaining the precise information needed to make the treatment work. A much larger expenditure in well drilling, monitoring, and hydrologic testing will be needed before any similar treatment efforts are conducted at this site. At Friendship Hill, the pre-treatment investigation would be even more extensive and costly because of the larger mine pool size, multiple discharges, and poorer water quality. Furthermore, such expenditures would be needed merely to assess the technical feasibility of the technique; the economic feasibility can be determined only after the treatment is successfully applied, when total costs can be quantified and compared to costs of conventional treatment. In-situ neutralization may yet prove to be cost-effective in mitigating acid drainage from abandoned underground mines, but only if the responsible party is willing to risk the initial investment needed to implement and optimize the process.

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