# Application of Aquifer Testing in Surface and Underground Coal Mines

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## ABSTRACT

The generation and transport of contaminated (acid) drainage from Appalachian coal mines depends heavily on the mechanisms by which water moves through surface mine spoils, underground mine openings, and the overlying fractured strata. In order to gain a better understanding of these flow mechanisms, slug tests, constant-discharge (pumping) tests, and chemical tracer tests have been employed at surface and underground mine sites. Aquifer testing in surface mine spoils has revealed that both Darcian and pseudokarst-type flow conditions are relatively common, and that conventional test analysis methods cannot always be successfully employed. Preliminary data analysis indicates that the extent of pseudokarst conditions and the hydraulic conductivity of the spoil material may be related to the overburden lithology, spoil age, and other geologic or mining factors. Aquifer testing in underground mines that have experienced widespread roof collapse suggests a flow scenario similar to surface mine spoils, where preferred flow conduit paths exist within a general diffuse flow system through the collapsed material. In flooded underground mines, where open mine entries constitute the primary flow paths, chemical tracer tests have been used to calculate flow velocities through the mine voids. Results of slug tests and pumping tests conducted in coal pillars and strata immediately above and adjacent to the mine openings are consistent with strata-mechanics theory, which predicts tensional zones and bedding plane separations in the strata immediately above and adjacent to a mine opening, and compressional zones in and above coal pillars between openings.

## INTRODUCTION

The production of acid mine drainage (AMD) from surface and underground coal mines is a widespread, persistent problem in Appalachia. In many cases, mine site hydrology is a key factor controlling the production and transport of AMD. However, many researchers who have attempted to understand and solve the AMD problem over the past 20 years believe that mine site hydrology is the most poorly understood aspect of the problem. This lack of understanding makes it difficult to achieve in-situ control of AMD via special handling of acidic spoils, addition of alkaline materials, or controlled flooding of underground mines. It also hinders efforts to utilize water within a mine spoil as a ground water resource in areas where AMD is not a problem, and increases the uncertainty associated with disposal of waste materials such as AMD treatment sludge and fly ash into abandoned underground mine voids. Over the past several years, the U. S. Bureau of Mines has conducted research aimed at characterizing the hydrology and geochemistry of the ground water systems in surface and underground mines. As a part of this research effort, aquifer tests were conducted at various mine sites in Pennsylvania and West Virginia. This paper describes how the aquifer tests were performed and how the results were interpreted to develop conceptual models of the somewhat unusual ground water flow systems within surface and underground mines.

## AQUIFER TESTING IN SURFACE MINE SPOILS

### Background

Mine spoil is a highly heterogeneous and anisotropic material. The heterogeneities are created in part by the processes of mining and subsequent reclamation. When dumped and/or regraded, the larger spoil particles tend to roll to the base of the spoil ridges, while the smaller particles stay on the sides and top (Rehm, et al., 1980). Differential settling and piping of the finer material begin shortly after regrading and contribute to the heterogeneous nature of spoil (Groenewold and

Bailey, 1979). Lithology of the spoil parent rock also plays an important role on the degree of heterogeneity and anisotropy. Sandstone parent rock, depending on the degree of induration, tends to form large blocky fragments and commonly weathers slowly to sand-sized particles. Limestone tends to break into large blocks during mining that weather relatively slowly. Weathering by-products of limestone are mainly dissolved solids that are removed from the mine site by outflow of groundwater. Shale, on the other hand, tends to break up into smaller fragments relative to the sandstone and limestone, and weathers more rapidly to yield clay and silt-sized material.

Generally, groundwater scientists working with surface mine spoil assume that they are dealing with a pure porous medium. Over an entire mine site and under steady state conditions, this assumption is valid; on such a large scale, mine spoil behaves similarly to unconsolidated glacial sands and gravels (Hawkins and Aljoe, 1990, 1991). However, Caruccio et al. (1984) first noted pseudokarst aquifer characteristics while excavating a test pit in a surface mine backfill. These pseudokarst characteristics are caused by the presence of voids and/or conduits within the spoil, and become a significant factor in the small-scale hydrology of a spoil aquifer. This is especially true when the aquifer is stressed by transient conditions or from aquifer testing.

## Discussion of Test Results

Slug tests (injection and withdrawal) were performed on over 40 wells from 8 surface mines in West Virginia and Pennsylvania. For slug injection tests, displacement was achieved by rapidly introducing a known volume of water or a solid into the test well. The slug withdrawal (bail) tests were performed by removing a known volume with a bailer or solid cylinder. The recovery of the well to the slug displacement was measured by use of a pressure transducer and a data logger. This allowed data to be collected continuously, accurately, and at a higher frequency than is possible manually; this was especially important for the portion of the tests immediately after slug injection or withdrawal. Each test was run until the water level reached or nearly reached the pre-slug level. Since the spoil aquifers were essentially unconfined, data analysis was performed by the method developed by Bouwer and Rice (1976) and Bouwer (1989) for unconfined aquifers.

Two distinctly different response characteristics were observed from the slug tests. One type of response was indicative of flow in a classical porous medium; the second indicated the presence of a pseudokarst flow system. In the latter response type, the almost instantaneous partial recovery of the slug displacement indicated the presence of voids or conduits in the vicinity of the well. Flow to or from the well during this rapid recovery was turbulent and could not be accurately analyzed by conventional (Darcian) methods. The unaccounted for slug dissipation-surface area of the voids contiguous to the test well can cause the hydraulic conductivity calculated by standard analysis methods to be greater than the actual value. Whenever analyzing data from aquifer tests in mine spoil these potential problems must be kept in mind. However, in spite of these problems, the aquifer parameters derived and the slug responses observed were still useful in the hydrologic characterization of mine spoil aquifers, as described below.

Figure 1 illustrates the "classic straight-line" response to slug displacement, which is indicative of a porous medium surrounding the test well. The recovery throughout the test follows a straight line on a semi-logarithmic scale, indicating diffuse flow between the well and the spoil aquifer. The displacement level calculated from the slug volume nearly coincides with the y-axis intercept of the regression line with the first data point. Approximately 40 percent of the wells tested exhibited a porous media-type response to the slug displacement.

The second type of aquifer response, shown in Figure 2, is substantially different from that expected for a pure porous medium. This response exhibits a recovery of a substantial percentage of the slug volume virtually as fast as possible given the physical constraints of the well construction. The volume of this early rapid recovery can exceed 99 percent. The remainder of the slug recovery, following the early rapid recovery, is a straight-line type similar to that of Figure 1.

The type of recovery shown in Figure 2 was termed the "dual recovery response" (DRR). Approximately 56 percent of the wells tested strongly exhibited this type of response (greater than 50 percent early loss). The remaining 4 percent of wells were in a "gray area" between the porous media-type response and the DRR.

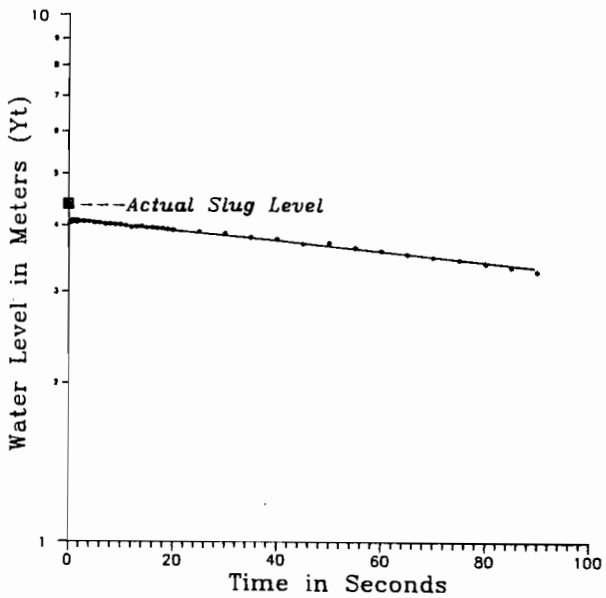


Figure 1. Slug test with typical porous-media recovery pattern.

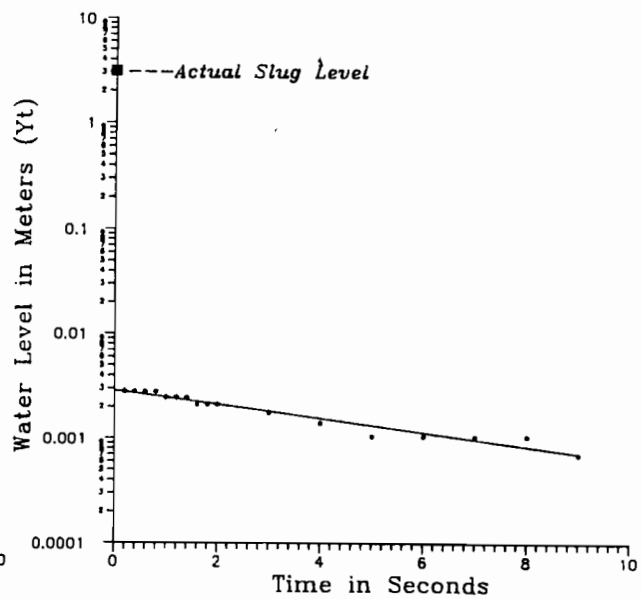


Figure 2. Slug test with atypical (DRR) recovery pattern.

For wells exhibiting DRR, the early rapid recovery was attributed to turbulent non-Darcian flow into and through large voids or conduits in a pseudokarst groundwater system. Borehole storage can account for only a small portion of the loss. The pseudokarst characteristics become significant because of the stress to the system caused by the instantaneous change in water level in the well. The latter straight-line recovery suggests that the conduits are discrete, poorly interconnected, and behave as if they are laterally finite; otherwise, the early (pseudokarst) recovery would be 100 percent in the majority of the cases.

The estimated hydraulic conductivity values calculated from the tests exhibiting DRR can be thrown off to some extent by the expanded area over which the change in head is dissipated, caused by the contiguous voids. Considering the formulae used by Bouwer and Rice (1976), the estimated hydraulic conductivity values obtained may be higher than actual values for the wells. Conversely, aquifer modeling performed on surface mine spoil indicates that the effective hydraulic conductivity for the site may be higher, by an order of magnitude, than the geometric mean of the values estimated by slug testing (Hawkins and Aljoe, 1990).

Ground water tracer tests likewise indicated that the conduits are discrete, and that diffuse porous media-type flow occurs between the voids and through the bulk of the spoil. Speed of groundwater movement through mine spoil was similar to that of unconsolidated glacial sand and gravel aquifers and significantly lower than that of true karst systems. The results of constant-discharge (pumping) tests likewise indicate that the effective hydraulic conductivity of a mine spoil is at least one order of magnitude higher than the values calculated from the slug tests. A more complete description of these aquifer tests is provided by Hawkins and Aljoe (1991). These differences are most likely caused by the potential incompatibility of the turbulent flow that occurs

during the early part of the slug test as well as an unquantified increase in the water dissipation surface area with the method used to analyze the slug test data. The analysis method assumes Darcian flow and a defined slug dissipation surface area. Although slug testing of mine spoil should not be abandoned, individuals involved with this type of testing should be cognizant of the potential problems involved. Given the aforementioned constraints slug tests still yield important estimates on aquifer properties of mine spoil.

## Mining and Geologic Influences

The estimated hydraulic conductivity values of surface mine spoil is directly affected by mining and geologic factors. The parent rock of mine spoil in the Appalachian coal fields is primarily sandstone, siltstone and shale; limestone usually is a minor constituent. Because of the lack of differentiation between shale and siltstone in most drill hole logs, these two lithologies were combined and noted as shale. For this study, percent sandstone was calculated by dividing the thickness of the sandstone by the total thickness of the overburden as shown by premining drill hole logs. Because of the difficulty of accurately determining the premining topography a volumetric percentage was not used. Given the post mining topographic conditions, the difference between the two is most likely small and insignificant.

The mining and geologic factors that appeared to have the greatest effect on spoil hydraulic conductivity were the lithology of the spoil material (or parent rock) and elapsed time since final grade reclamation was achieved. These data were plotted on notched box-and-whisker plots to illustrate the observed trends. In notched box-and-whisker plots, the bottom and top of the box correspond to the first and third quartiles of the data (the central 50 percent of the data are contained within the box). The lines, or "whiskers" on the box ends extend to the last observation within 1.5 times the interquartile range from the end of the first and third quartile. Any value lying between 1.5 and 3.0 times the box width beyond the box ends is considered a possible outlier and is plotted with a square. Any point beyond 3.0 times the interquartile range from the end of the box is considered a far outlier and is marked with a plus sign (+). Within each box, the horizontal line denotes the median of the data and notches in the sides represent the 95% confidence interval around the median. The median rather than the mean is used because it is commonly a better indicator parameter of central tendency of the data. The width of the box is proportional to the square root of the number of observations in that group. For additional information on box plots the reader is directed to McGill and others (1978).

Figure 3 is a notched box-and-whisker plot comparing the percent of sandstone to the negative log of the hydraulic conductivity. The lower values on the y-axis indicate higher values of hydraulic conductivity and vice versa. The sites were divided into three categories of percent sandstone by volume (0-50, 51-75, and 76-100%). The greatest variation of hydraulic conductivity about the median, in terms of the first and third quartiles as well as the 95% confidence interval, occurs in spoil that is from 0 to 50% sandstone, the second largest occurs in spoil with 51-75% sandstone, and the least variation occurs in spoil that is 76 to 100% sandstone.The median hydraulic conductivity in Figure 3 is successively higher for each group as the range of sandstone percent increases. This is explained by the hydraulic properties of the different lithologies and the method by which the overburden material was spoiled. Because shale-rich spoil zones are composed of smaller fragments that weather and breakdown to silt- and clay-sized particles the hydraulic conductivity will be lower than sandstone-rich zones where the initial spoil fragment sizes are much larger and the weathering by-products are larger (sand-sized) than those from shales. The processes of mining and reclamation facilitate the spoil heterogeneity by creating zones of predominantly one lithology or the other. Overburden is often removed in layers by dragline or bulldozer, therefore discrete zones composed of a single lithology are common. These mono-lithologic zones are also created by the tendency of large spoil fragments to accumulate at the base of spoil ridge and the tendency of sandstone to break into larger fragments than shale. A test well drilled into the spoil backfill with a lithology of half sandstone and half shale has an equal chance

of intersecting a predominantly sandstone or shale zone therefore the hydraulic conductivity is expected to range widely. The decreased median is caused by the increasing number of wells intersecting the shale zones as the shale percent increases.

The narrower first and third quartile range and corresponding 95% confidence interval about the median are accompanied by higher median values as the sandstone percent increases from the 0 to 50% to the 51 to 75% range and then to the 76 to 100% range. As the sandstone percent increases, spoil becomes less heterogeneous causing a reduction of broad the hydraulic conductivity range. The higher median hydraulic conductivity is caused by less test wells intersecting shaley zones and more intersecting the higher transmissive sandstone rich spoil.

Figure 4 is a notched box-and-whisker plot relating hydraulic conductivity to the elapsed time since final grade reclamation was achieved. The median for sites that have been reclaimed for less than 30 months is significantly lower than the median for sites that have been reclaimed for over 30 months. For notched box-and-whisker plots, if the notches about the median of two box plots do not overlap then the medians are said to be significantly different at the 95 percent confidence level. The higher hydraulic conductivity exhibited by sites that have been reclaimed for a longer period of time is directly related to the formation and accentuation of large voids and conduits over time by differential settling and piping of the fine grained spoil material. Groundwater has a tendency to follow the path of least resistance which are these large voids that once enlarged allow more rapid movement of groundwater. These voids form over time mainly by the vertical movement of recharging waters and horizontal movement of groundwater in the saturated zone. In the first two years or so after reclamation the water table is still in the process of re-establishing. Recharge from the surface is lower than natural conditions because of the lack of soil structure, soil compaction, and low vegetative growth (Razem, 1983). The time required for the water table to rebound also depends on precipitation frequency, intensity, and duration. After 30 months or more, the re-establishing groundwater table and increasing surface recharge facilitate the development of voids that make the hydraulic conductivity significantly greater than that exhibited shortly after reclamation. These results are preliminary, and other interpretations are possible. Additional research may reveal other factors that contribute to the observed trends.

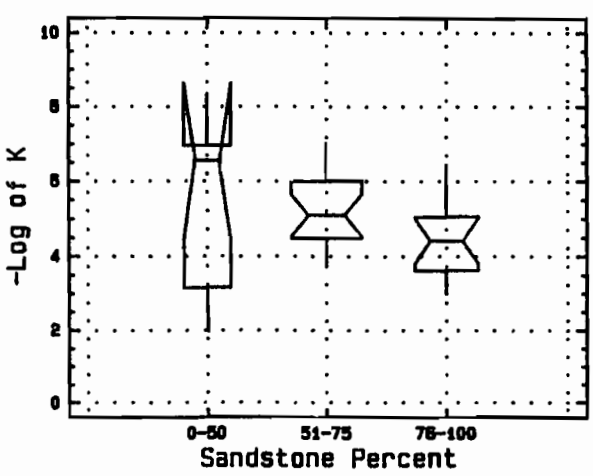


Figure 3. Effect of sandstone percentage on spoil hydraulic conductivity.

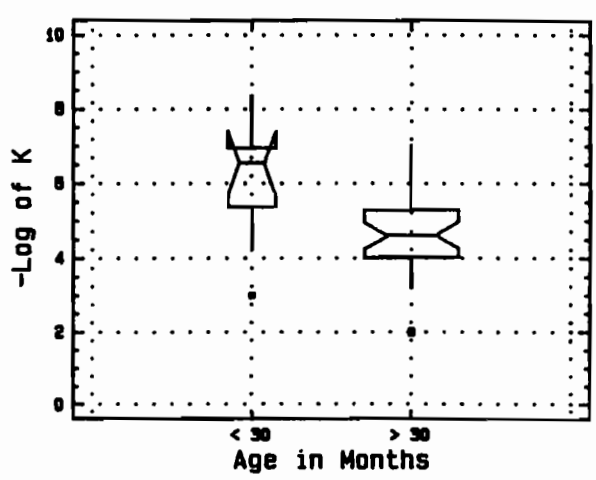


Figure 4. Effect of spoil age on spoil hydraulic conductivity.

## Description of Mine Pool Aquifers

A great deal of research has been conducted on the effects of underground coal mining on aquifers, and numerous aquifer tests have been conducted in mine-affected strata. In most cases, however, the aquifers of interest have been located in the overburden strata above the mine, and the primary concern has been the loss of water from supply wells located in these strata. Comparatively little work has been done to characterize the hydrologic behavior of mine pools, which typically comprise the mine workings (intact or collapsed) and the strata immediately above and adjacent to them. From an environmental standpoint, the mine pools of greatest concern are those which discharge acidic water to the surface through abandoned mine portals, boreholes, or fractures that intercept the pool.

If most or all of the entries near the mine discharge area have collapsed completely, an aquifer that is similar to a mine spoil aquifer may develop. A mine pool of this type was recently described by Aljoe and Hawkins (1991a). The caved material provided enough resistance to flow to allow the establishment of a regular, stratigraphically-controlled water table gradient, but preferred flow pathways analogous to the pseudokarst conduits described earlier still existed. Wells completed within the caved material responded to slug tests in a manner similar to those in surface mine spoil -- some wells exhibited a regular recovery (hydraulic conductivities of $2.6 \times 10^{-3}$ to $3.9 \times 10^{-5}$ ft/min), while others recovered so rapidly that conventional analytical procedures could not be applied. A bromide tracer test revealed a strong hydrologic connection between two wells that were located along the same collapsed mine entry (flow velocity greater than 14 ft/day), but did not reveal a similar connection between these wells and the mine discharge.

If the mine discharge is sealed and the entries remain mostly intact, an "underground reservoir" may develop, as depicted in Figure 5 for a mine site in western Pennsylvania. The open entries serve as a basal drain system for the reservoir, and the underclay beneath the coal seam provides a slope toward the portal area that governs the direction of flow. The piezometric surface defined by wells penetrating the mine pool is essentially horizontal; flow toward the discharge area occurs not because of a measurable hydrologic potential gradient in a porous medium, but because the mine voids are connected to the atmosphere at an elevation that is lower that of the reservoir surface. In Figure 5, a borehole near the portal area and slow leakage through the portal seals provide this connection; in other mines, a shaft or fractures may serve this purpose. The borehole provides a relatively unimpeded discharge path, which limits the upward rise of the mine pool in a manner analogous to the spillway of a surface water reservoir.

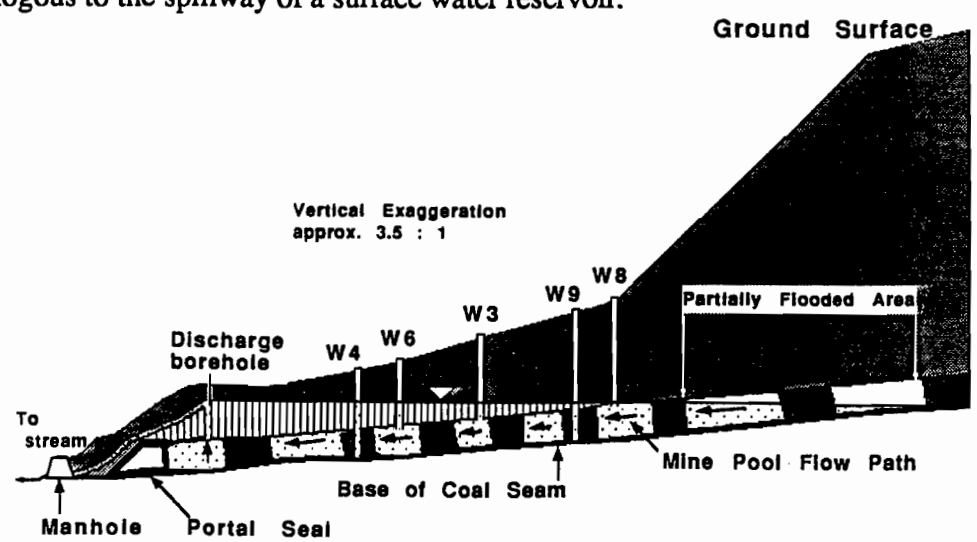


Figure 5. Hypothetical reservoir flow pattern in an underground mine pool.

The type of mine pool depicted in Figure 5 is of considerable interest because its conduit-type flow system makes it more amenable to in-situ acid mine drainage treatment schemes such as alkaline injection (Aljoe and Hawkins, 1991b). A mine with this type of pool is also interesting in terms of waste disposal because it has well-defined zones that are that are likely to remain completely submerged or consistently dry; either setting may be desirable, depending on the characteristics of the waste to be disposed. The aquifer testing used to evaluate the flow system within the mine pool depicted in Figure 5 is discussed here.

## Mine Background and Description

The three main portals of the underground mine at the study site (Figure 6), which is located in western Pennsylvania, were sealed about 20 years after mine closure in a deliberate attempt to flood the mine. However, the hydrostatic pressure of the mine pool eventually forced a surface "blowout" at a point about 150 ft behind the portal seals; the borehole shown in Figures 5 and 6 was installed to collect the mine discharge at this point. Flow from this borehole normally

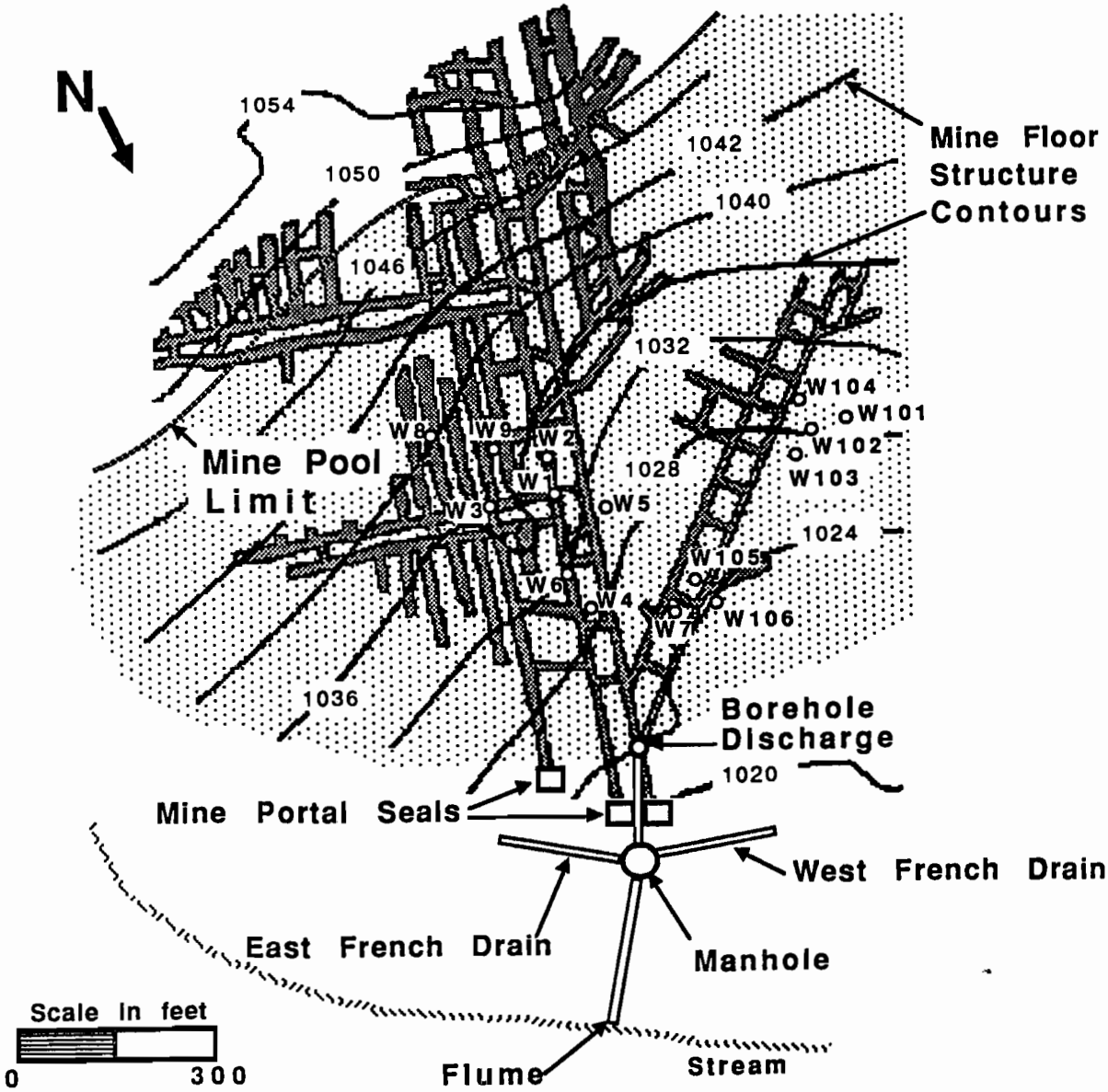


Figure 6. Plan view of underground mine pool study site.

constitutes about 75-80% of the total mine discharge, with the remainder emanating from two french drains that collect gradual seepage of mine water that leaks around and through the portal seals. The flows from the french drains and the borehole are routed to a manhole, and the combined discharge is sent to a nearby surface stream. Five of the fifteen monitoring wells installed at this site (1, 2, 3, 6, and 8) intercepted open mine voids, and the rest penetrated solid coal in between or adjacent to the voids. The latter were screened to remain open only to the 10 ft of strata immediately above the underclay, except for wells 102 and 105, which were open only to the 5-ft coal seam. Aljoe (1992) describes in detail how the mine discharge rates, pool elevations, precipitation data, water quality data, aquifer testing, and qualitative field observations were used to develop and validate the ground water flow system at this site. The important role of aquifer testing -- tracer tests, slug injection tests, and pumping tests -- in this evaluation is described here.

## Tracer Tests

Conduit flow through the open mine voids was believed to be dominant, and chemical tracer tests were performed to determine the flow velocity through various segments of the pool. Initially, it was assumed that all mine entries at the same structural elevation carried the same percentage of the total mine pool flow. Under steady flow conditions, the total volume of water passing through the voids would be the same at all elevations; since fewer mine entries existed at lower elevations, flow velocities were expected to be greater in entries that were closer to the discharge.

### Well 3 Bromide Tracer Test

Bromide was the preferred chemical tracer for this site because it is conservative and stable in AMD. Background concentrations of bromide were negligible, and bromide concentrations as low as 0.1 mg/L could be detected by available laboratory equipment. Well 3 was chosen for the initial bromide tracer test because it was directly connected to the vast majority of upgradient voids, and was farther upgradient than any other void well of this type (well 8 was farther upgradient but was believed to be located within a "blind" entry - see Figure 6). Under uniform flow conditions, the flow velocity through all mine entries at the same structural elevation as well 3 would have been approximately 25 ft/day, based on the mean mine discharge rate during the first three months after tracer injection. However, the application of a borehole dilution equation (Drost, et al., 1968; Grisak, et al., 1977) to the bromide decline in well 3 yielded an estimated flow velocity of only about 1 ft/day in that entry (Aljoe and Hawkins, 1991a). At this velocity, traces of bromide would have been expected in well 1 after 100 days and well 6 after 250 days; however, no trace of bromide was ever detected at wells 1 and 6 after more than 300 days of sampling. This suggested that well 3 did not have a direct hydrologic connection to wells 1 or 6. to wells 1 or 6. Furthermore, the slow flow velocity suggested that only a small portion of the total discharge flow (estimated at about 1%) was occurring through the entry at well 3; this obviously refuted the uniform flow assumption. It was not surprising, therefore, that no trace of bromide was detected at the borehole discharge.

### Alkaline Injection - Sodium Tracer Data

In an attempt to neutralize the acid mine water within the voids, about 2000 gallons of 25% sodium hydroxide solution (1890 kg of NaOH) were injected into the mine pool about three months after the well 3 tracer test. 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. Despite the failure of alkaline injection to achieve its intended purpose (Aljoe and Hawkins, 1991b), the high quantities of injected sodium served as a useful tracer.

Figure 7 shows that sodium concentrations at the borehole discharge remained relatively constant, except for the three months immediately following alkaline injection. Within this period, distinct sodium peaks occurred at 7 days and 49 days after injection. If Peak 1 in Figure 7 represents the passage of sodium from well 6 through the borehole discharge, the mean flow velocity through the lower portion of the mine pool can be estimated at about 46 ft/day. Similarly, if Peak 2 represents the discharge of sodium injected at well 3, the mean flow velocity through the entries between well

3 and the discharge can be estimated at about 11.3 ft/day. These results were consistent with the conduit flow assumption for this mine, wherein flow velocities would be expected to increase in the vicinity of the discharge.

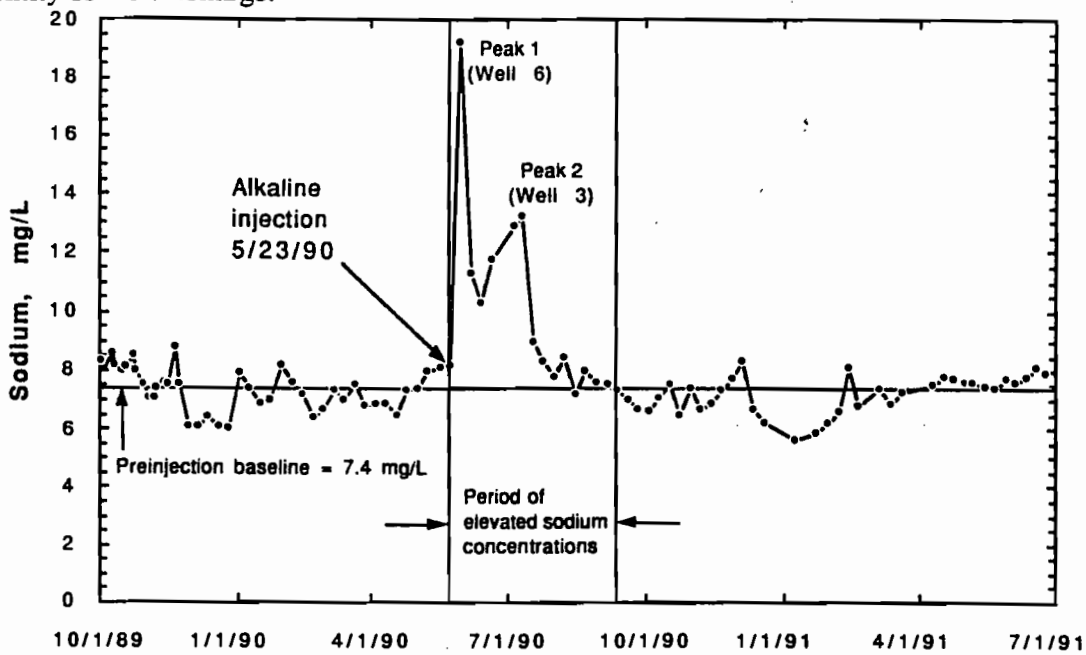


Figure 7. Sodium tracer breakthrough at mine discharge.

Despite the existence of discernible sodium peaks in Figure 7, the observed sodium concentrations and loadings were much lower than would have been expected. Further examination of the mine map (Figure 6) and other water quality data suggested that the mine entries in the vicinity of wells 3 and 6 may have been only a minor source of water to the discharge borehole. Mass-balance calculations using sodium concentrations before and after alkaline injection indicated that only 1.3% of the borehole flow originated from this source; the rest was believed to originate from the two-entry system near wells 101-106 (which had not yet been drilled), with substantial mixing and dilution occurring in the west main entry of the mine prior to discharge.

Although sodium concentrations in wells 3 and 6 returned to pre-injection levels within six weeks after alkaline injection, it was estimated that only 6 percent of the injected sodium had passed through the borehole discharge during the elevated-sodium period shown in Figure 7. Sodium is not a particularly conservative tracer in mine water; however, a significant degree of water quality stratification was noted in all the mine voids at this site, suggesting that internal mine pool flow patterns as well as chemical processes may have been responsible for the poor sodium recovery.

Well 6 Bromide Tracer Test

During the first two tracer tests, the borehole was the only discharge point sampled because flows from the french drains (Figure 6) were observed to be negligible. However, a "breakthrough" in the mine portal seal area that occurred about 6 months after alkaline injection significantly increased the flows from the french drains and decreased the percentage of flow from the borehole (Aljoe, 1992). The simple mixing and discharge scenario described above was no longer considered to be a complete description of the flow patterns within the mine voids. It was suspected that the two-entry system near wells 101-106 supplied most or all of the flow to the discharge borehole, while the main entries in the vicinity of wells 3 and 6 discharged primarily to the french drains. A second bromide tracer test, using well 6 for tracer injection, was conducted to confirm this postulated hydrologic connection.

Bromide data collected by a continuous sampler at the manhole outlet are summarized in Figure 8. The bromide profiles were typical of a "plug flow" system; the initial steep rise to a strong, early peak suggested that very little dispersion had occurred prior to tracer arrival at the detection point. The peak bromide concentration occurred on the seventh day after tracer addition, versus the fifth day for loading, primarily because flows on the fifth day were much larger. The estimated flow velocity between well 6 and the mine discharge was 46 to 65 ft/day, depending on whether concentration or loading were used to define the peak. This agreed with the previous velocity estimated from sodium data despite the observed changes in discharge patterns.

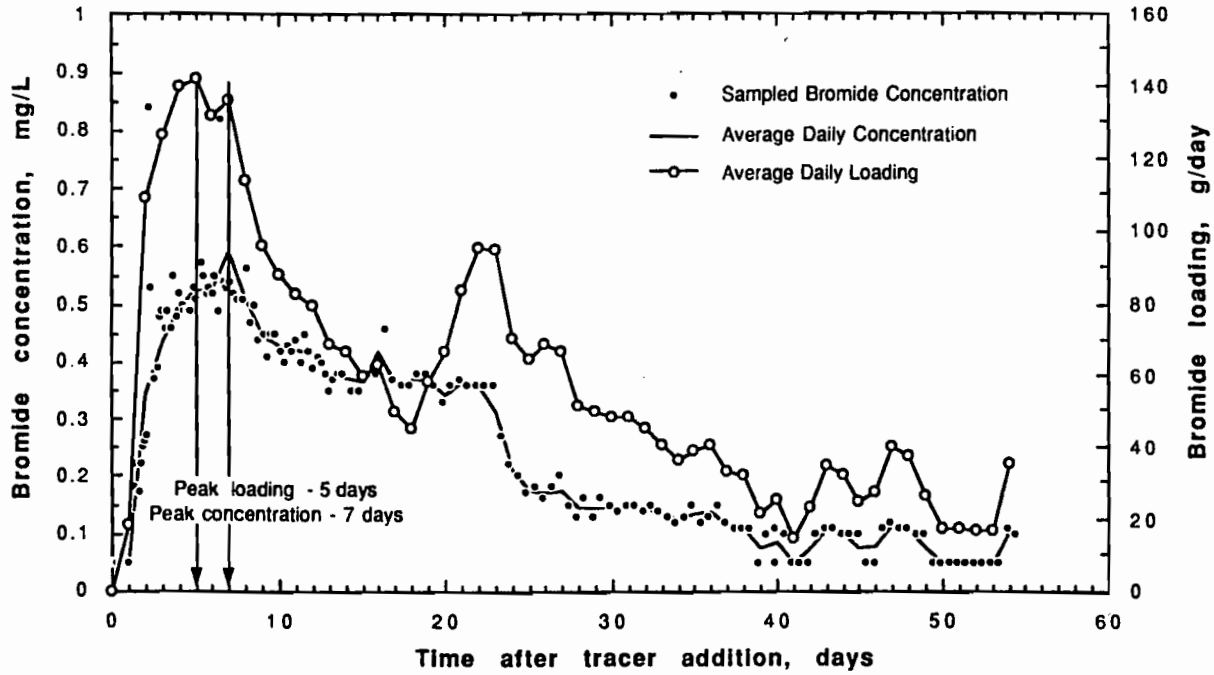


Figure 8. Well 6 bromide tracer test results - manhole outlet.

Bromide appearance in the three discharge sources (borehole and two french drains) suggested that portions of the tracer cloud had followed different pathways, with the path to the west french drain being the most direct. For example, the highest bromide concentration in any discharge sample (6.8 mg/L) occurred in the west french drain on the third day after tracer addition; concentrations at this location decreased consistently thereafter. Conversely, bromide concentrations in the east french drain increased steadily during the first 17 days after tracer addition, and remained relatively constant (close to 1.0 mg/L) through the 54th day. Concentrations in the east french drain consistently exceeded those of the west french drain after the 13th day. This gradual release pattern suggests a slower flow path to the east french drain, with greater dispersion of bromide along the path. Bromide concentrations in the borehole discharge were negligible, confirming that the original main entries of the mine discharged to the french drains but not to the borehole.

The aforementioned borehole dilution equation was applied to bromide data collected from the top, middle and bottom of the well 6 entry. The flow velocity at the bottom (8.75 ft/day) more than four times greater than at middle or top; this implied a flow scenario whereby the entry penetrated by well 6 discharged to the french drains through leaks in the base of the portal seals. Using the average bromide concentration at the three locations in the borehole dilution equation yielded a flow velocity in the well 6 entry (4.66 ft/day) that was more than 4 times greater than in the well 3 entry, but an order of magnitude less than the average velocity between well 6 and the discharge. These results again confirmed that flow velocity increased in the vicinity of the discharge.

After 54 days of sampling, only 13.6% of the bromide mass added to well 6 was recovered at the manhole outlet, and an additional 14.5% could be accounted for by assuming that the bromide had become uniformly dispersed among all mine entries downgradient of well 6. According to Davis, et al. (1985), it is unlikely that precipitation, absorption, and adsorption would remove substantial quantities of bromide from the mine pool flow system. Therefore, the fate of the "missing" bromide, over 70% of the total added mass, was somewhat problematic. One possible explanation is that pockets of high-bromide water have settled within localized dips the floor of the mine between well 6 and the discharge; a significant degree of water quality stratification was noted in well 6 and all other voids at this mine. At the average calculated flow velocity through this reach of the pool (46-65 ft/day) the associated turbulence would probably be insufficient to flush the bromide from these pockets. This may also explain why only 6 percent of the sodium added by alkaline injection was recovered.

## Slug Injection Tests

One purpose of the slug injection tests was to provide a means for characterizing the type of flow occurring within the saturated, solid portion of the mine pool reservoir. For example, the vast water quality differences between the void wells and those in the adjacent solid material suggested that very little lateral hydrologic communication existed between the two, and that recharge to the solid material came primarily from above. This suggested that the strata around the mine openings could be conceptualized as a simple unconfined aquifer. If this were the case, the slug test recovery would be easily modeled by the equation developed by Bouwer and Rice (1976). However, the presence of conduit flow in the voids at a piezometric level that was far above that of the mine roof suggested that elements of a confined flow system were also present. If the aquifer around the tested wells were confined, the response would follow the form described by Cooper, et al. (1968) for confined flow systems.

Except for wells 101 and 103, all wells recovered in the straight-line fashion typical of unconfined aquifers; the only substantive differences were the overall lengths of the straight-line recovery periods and corresponding hydraulic conductivities (Table 1). Attempts to fit the recovery data to

Table 1. Summary of Slug Injection Test Results

| | | Well No. | Portion of Data Used, min. | Hydraulic Conductivity (K), ft/min |
|---|---|---|---|---|
| | PILLAR WELLS | 4 | $.20 < t < 62$ | 1.89E-04 |
| | | 7 | $.25 < t < 60$ | 3.03E-04 |
| | | 9 | $.75 < t < 60$ | 4.65E-05 |
| | | 105 | $.20 < t < 20$ | 1.33E-03 |
| WELLS IN ADJACENT STRATA | Regular Response | 5 | $.20 < t < 6.5$ | 1.58E-03 |
| | | 102 | $.20 < t < 34$ | 1.12E-03 |
| | | 104 | $.067 < t < .167$ | 9.96E-02 |
| | | 106 | $.13 < t < 1.67$ | 1.15E-02 |
| | Irregular Response | 103 | $.15 < t < 30$ | 7.84E-04 |
| | | 101 | $1.0 < t < 5.0$ | 1.58E-03 |
| | | 101 | $10 < t < 35$ | 2.86E-04 |

**Geometric Average Hydraulic Conductivity**

**Pillars: 2.44E-04 ft/min**

**Adjacent Strata: 6.71E-03 ft/min**

the type curves of the Cooper, et al. analysis method resulted in much poorer matches. The unconfined aquifer model thus more accurately described the slug injection response. This result alone did not "prove" that the solid material around the mine voids was an unconfined aquifer; however, it did suggest that vertical as well as lateral flow could have been responsible for the observed water quality differences between the voids and the surrounding solid material. Wells 101 and 103 responded in an erratic manner that did not closely follow either recovery pattern; further investigation of these wells is necessary to fully interpret their responses.

A second purpose of the slug injection tests was to determine whether variations in hydraulic conductivity in the wells could be related to their locations with respect to the mine voids. As discussed by Booth (1986), strata immediately adjacent to a mine opening experience primarily tensile stresses, while the strata between two mine openings experience primarily compressive stresses. Therefore, the hydraulic conductivity measured in wells completed in the strata adjacent to the mine openings (wells 5, 101-104, and 106) would be expected to be greater than in wells located in pillars (wells 4, 7, 9, and 105), which were surrounded completely by mine entries. Field experience in bailing all these wells prior to sampling provided qualitative evidence of this, but the slug injection tests provided a means for quantifying these differences.

Table 1 shows that the average hydraulic conductivity measured in wells adjacent to the mine voids was indeed more than an order of magnitude greater than in the pillar wells ($6.71 \times 10^{-3}$ vs. $2.44 \times 10^{-4}$ ft/min), in accordance with strata mechanics theory. The highest hydraulic conductivities were measured in wells 104 and 106; these wells were closer to the mine voids than the other "adjacent strata" wells. Water quality data suggested that recharge to these wells was provided by a consistent AMD source that was similar in quality to that of the borehole discharge (presumably the adjacent mine entries). However, the slug test responses suggested that this recharge did not come via direct release from confined storage within the voids, but followed a more circuitous path through the intervening strata.

## Pumping Tests

Short-term (3-hour) pumping tests at rates of 5-6 gal/min were conducted in wells 104 and 106 to further assess the nature of the flow system adjacent to the mine voids and to provide an initial check on the strength of the hydrologic connection between the wells and the voids. Drawdowns in three monitoring wells close to well 106 (wells 105, 7, and 5) were insignificant throughout the test; this was expected, since there is at least one mine opening between well 106 and these monitoring wells. Drawdowns were also insignificant in two of the three wells near well 104 (101 and 103). However, drawdown in well 102, which is closest to well 104 and is open only to the coal, occurred within a few minutes after the start of pumping and increased consistently to about 0.1 ft. by the end of the test.

Preliminary evaluation of the pumping test data from well 104 suggests that elements of a confined flow system may be present within the coal seam adjacent to the mine voids, but that significant flow from the mine voids and/or vertical flow through the overlying saturated strata occurred during pumping. For example, the hydraulic conductivity of the material between wells 102 and 104 can be represented by the average of the values in Table 1. In this case, the observed drawdown in well 102 at the end of the test was about 20 times less than that predicted by using the Theis (1935) equation for ideal, confined aquifers, but 5 to 10 times greater than the drawdown predicted by using the solution of Neuman (1975) for isotropic unconfined aquifers. If the aquifer were modeled as an anisotropic unconfined aquifer using the Neuman solution, the ratio of the vertical to the horizontal hydraulic conductivity would have to be about 0.2 in order to provide general agreement between the predicted and measured drawdowns. Attempts to fit the time-drawdown data from well 102 to a variety of graphical solutions for confined and unconfined aquifers failed to yield a clear match; however, the closest agreement was achieved by using the method developed by Cooper and Jacob (1946) for confined aquifers, after first correcting the

observed drawdowns to approximate unconfined conditions. The hydraulic conductivity calculated by this method was 0.12 $ft^2$/min, about the same as that listed in Table 1 for well 104.

The water quality of both pumped wells remained very consistent throughout the pumping tests, and was very similar to that of the borehole discharge. This supported the hypothesis of easy recharge from the mine voids to the wells. Longer pumping tests and more sophisticated analytical procedures (e.g., leaky aquifers and image-well methods) may be employed in the future to refine the conceptual description of the flow process.

## SUMMARY AND DISCUSSION

Slug tests performed in surface mine spoil yielded two types of aquifer recovery response; some responses indicated a porous medium surrounding the wells, while others exhibited a dual recovery response (DRR) which suggests pseudokarst effect within a diffuse flow groundwater regime. The nearly instantaneous partial to full recovery in the DRR wells indicated the presence of large voids or conduits within the spoil. These heterogeneities cause problems in the calculation of hydraulic conductivity from slug tests. The expanded surface area for the dissipation of the slug displacement can cause the hydraulic conductivity estimation to be higher than actual values. The large voids facilitate rapid, turbulent flow to or from the well, and act as a source or sink of slug water. Because the hydraulic conductivity calculation is based on Darcy's Law, aquifer parameters may not be accurate when turbulent flow occurs. Despite of the problems involved with slug testing, the aquifer parameters derived and the slug responses observed are extremely important in the hydrologic characterization of surface mine spoil.

The lithology of the spoil parent material influences the hydraulic conductivity of the spoil aquifer. Increasing sandstone percent yields higher median hydraulic conductivity values with smaller interquartile ranges and confidence intervals about the median. These differences are caused by segregation of lithologic units during mining and reclamation and by differences in the spoil weathering by-products. These mono-lithologic zones cause large differences in the transmissive properties of mine spoil. Age of spoil also has a strong influence on its hydraulic conductivity. By the 30 month period the formation of large voids and conduits cause the median hydraulic conductivity to be significantly higher at the 95 percent confidence level. These voids develop slowly in the first 30 months because of the lower recharge rates and the still rebounding water table.

Tracer tests conducted in a flooded, abandoned underground coal mine in western Pennsylvania yielded average flow velocities of about 11 to 65 ft/day (1 to 8 ft/day in individual entries), with higher velocities occurring through sections of the mine pool which were closer to the discharge. These velocities were about an order of magnitude slower than those reported by Aldous and Smart (1988) for flooded workings in British coal mines. This difference is attributed to the unmeasurably low hydraulic gradients within the mine pool at the Pennsylvania site. Flow velocities at the bottom of the mine voids were greater than at the top, but apparently not great enough to prevent entrapment of substantial quantities of unreacted tracer within the voids, perhaps within isolated "pockets" along the mine floor. Entrapment of tracer within fractures penetrating the mine voids or loss of tracer via leakage through the underclay was also possible, but this could not be verified with available data. The slow movement of water in the monitored portion of the mine pool and apparent storage of unreacted ions adversely affects attempts to treat this contaminated water via in-situ techniques. However, the apparent ability of this pool to provide storage and dilution of injected products may be advantageous in terms of waste disposal in the voids.

Slug injection and tests within the saturated, solid material surrounding the underground mine voids showed that the hydraulic conductivity in strata adjacent to the voids was more than an order

of magnitude greater than in the pillar wells ($6.71 \times 10^{-3}$ vs. $2.44 \times 10^{-4}$ ft/min), in accordance with strata mechanics theory. Flow through this material could best be characterized as unconfined, and was largely independent of the observed conduit flow through the nearby mine voids. However, pumping tests and water quality data in the wells on the downgradient side of the voids provided evidence of at least some hydrologic communication in this area. Further research must be conducted to fully characterize the flow regime and to determine the potential for long-term migration of contaminated water from the mine voids through the surrounding solid material.

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