HYDROLOGIC AND WATER QUALITY CHARACTERISTICS OF A PARTIALLY-FLOODED, ABANDONED UNDERGROUND COAL MINE[1]

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Abstract: The hydrologic and water quality characteristics of a partially flooded, abandoned underground coal mine near Latrobe, PA, were studied to support the development of techniques for in situ abatement of its acidic discharge. A quantitative understanding of the conditions affecting discharge flow was considered to be very important in this regard. Statistical analysis of hydrologic data collected at the site shows that the flow rate of the main discharge (a borehole that penetrates the mine workings just behind a set of portal seals) is a linear function of the height of the mine pool above the borehole outlet. Seepage through or around the portal seals is collected by a set of french drains whose discharge rate is largely independent of the mine pool elevation. This seepage was enhanced after a "breakthrough" that occurred during a period of unusually high pool levels. The mine pool recharge rate during winter is about 2.5 times greater than that of any other season; recharge rates during spring, summer, and fall are approximately equal. Mine pool and discharge water quality information, along with bromide tracer tests, suggest that the original main entries discharge primarily to the french drains, while the borehole carries the discharge from an unmonitored set of entries northwest of the mains. The water quality of the east french drain discharge may have been improved substantially after seepage through the alkaline materials used to construct the portal seals.

Additional Key Words: acid mine drainage, mine pools, statistical analysis

Introduction

Small-scale mine site hydrology is one of the most poorly understood aspects of the acid mine drainage (AMD) problem. This makes it difficult to achieve in situ control of AMD and increases the uncertainty associated with disposal of waste materials such as AMD treatment sludge and fly ash into abandoned underground mine voids. This paper describes how the hydrologic and water quality data from a partially-flooded underground mine near Latrobe, PA, were used to characterize the "mine pool aquifer" and delineate probable flow paths through the mine. The study site, located within Keystone State Park, was described previously by Aljoe and Hawkins (1993). The mine pool (figures 1 and 2) was formed when the portals of an updip, free-draining underground coal mine were sealed in the early 1970's. The pressure of the impounded water eventually caused a breakout through the land surface approximately 45 m behind the seals. A borehole was installed at this point to allow a relatively unimpeded outlet for the mine discharge, thus limiting the further buildup of water within the mine. The open mine entries serve as a basal drain system which carries most of the flow; the orientation of the entries and the slope of the underclay governs the direction of flow. Flow toward the discharge occurs not because of a measurable hydrologic potential gradient within the mine pool, but because the pool is connected to the atmosphere (via the borehole) at an elevation that is lower than that of the pool surface. Seepage through or around the portal seals is collected by two french drains, providing another outlet for the mine discharge.

Mine Pool Elevation and Discharge Characteristics

In the initial hydrologic investigation at this site (October 1989 through December 1990), it appeared that the total mine discharge was related linearly to the elevation of the mine pool (Aljoe and Hawkins 1993). This suggested that the pool elevation could serve as a good predictor for the discharge rate using simple linear regression. Such a predictive capability would be valuable for long-term data collection because pool elevation can be measured and recorded easily in a borehole with a pressure transducer and datalogger. Conversely, direct measurements of mine discharge are typically more labor-intensive to obtain over the long term because the primary discharge structure (weir, flume, calibrated pipe, etc.) requires frequent cleaning and other maintenance, especially in AMD environments where iron hydroxide buildup is rapid.

A nonparametric line-fitting technique first described by Theil (1950) and refined by Conover (1980) was found to be more appropriate than the more commonly used ordinary least squares (OLS) technique for developing a linear

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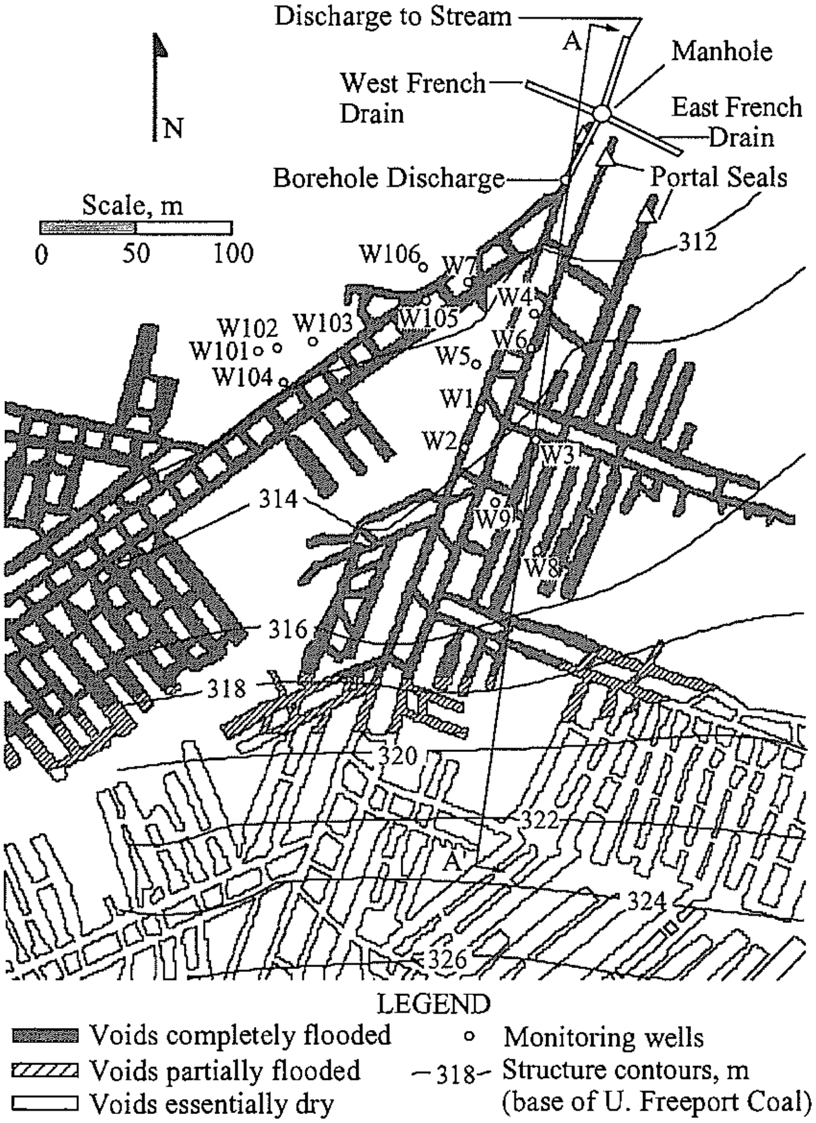

Figure 1. Map of study mine and discharge features

equation relating the discharge rate (Q) to the pool height (h). Although the OLS technique yielded a regression coefficient of 0.96 using the initial Q and h data, its validity was questionable because the position of the regression line was strongly controlled by four data points with very large Q and h values. Attempts to reduce the influence of these points by transforming the data (logs, square roots, etc.) were unsuccessful. Helsel and Hirsch (1991) provide an excellent discussion of the problems associated with this situation, and recommend the use of nonparametric techniques when it occurs. The slope of the Theil line (β_1) is defined as the median of all the $n*(n-1)/2$ pairwise slopes associated with a data set of n pairs:

$$\beta_1 = \text{median}\ (Q_j - Q_i) / (h_j - h_i) \qquad (1)$$

for $i < j$; $i = 1, 2, \ldots (n-1)$; $j = 2, 3, \ldots n$.

The intercept of the Theil line, β_0, is

$$\beta_0 = [\text{median}\ (Q)] - [\beta_1 * \text{median}\ (h)]. \quad (2)$$

For the data collected in the initial investigation, the values of β_0 and β_1 were 4.28 and 13.91 respectively, with Q expressed in L/min and h in cm, referenced to the top of the discharge borehole. The resulting linear regression equation using the Theil slope and intercept was

$$Q = 4.28 + (13.91 * h). \qquad (3)$$

However, equation 3 proved to be a poor predictor of the subsequent discharge flows because the hydrologic behavior of the mine pool appeared to change substantially after equation 3 was developed.

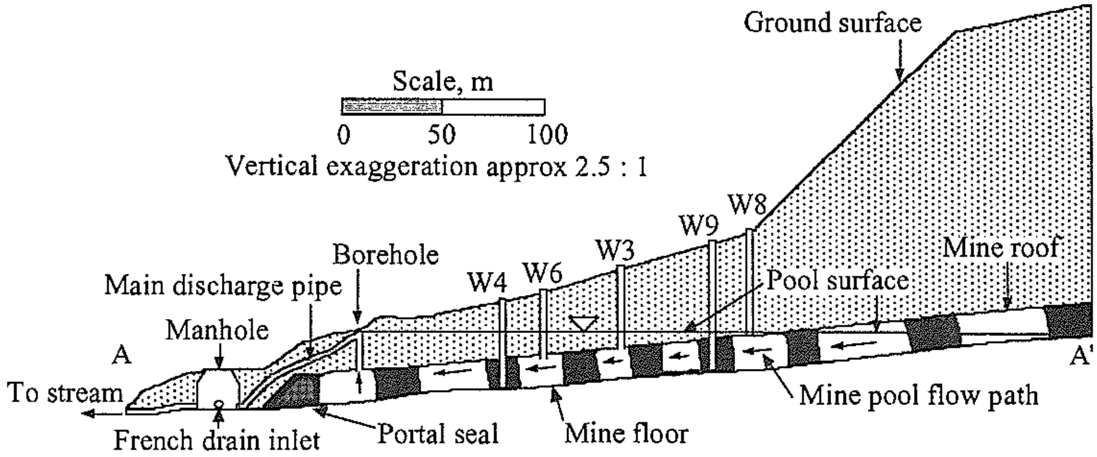

Figure 2. Cross-section of mine pool study site.

As shown in figure 3(a), the pool elevation dropped far below the top of the borehole in the late summer and fall of 1991 and 1992, but had not done so during 1989 and 1990. Also, the maximum pool elevations reached during the winters of 1991-92 and 1992-93 were more than 24 cm below the maxima of the two preceding winters. These changes could not be traced to precipitation differences; it was therefore postulated that they were related to a significant change in the mine discharge conditions.

Note in figure 3(a) that an anomalous data period occurred during December 1990-January 1991. This period is magnified in figure 3(b); a detailed discussion of these events is provided by Aljoe (1992) and is summarized here. Hourly water levels obtained from a pressure transducer in one of the mine void monitoring wells (W2) revealed several very sharp declines and rises in the pool elevation during this period. On two occasions, the pool elevation actually dropped <u>below</u> the top of the discharge borehole, although flows were consistently greater than at any time during the study period. Independent measurements of the pool elevation in wells 1, 6, and 8 confirmed that the W2 hydrograph was indicative of the overall pool elevation, and that the observed rapid fluctuations were not related to the subsequent transducer failure on January 19. The erratic pool behavior was interpreted as a breakthrough in the portal seal area, resulting in a permanent increase in flow to the french drains; this interpretation was supported when, in the fall of 1991, flows from the french drains became visibly discernable for the first time during the study period.

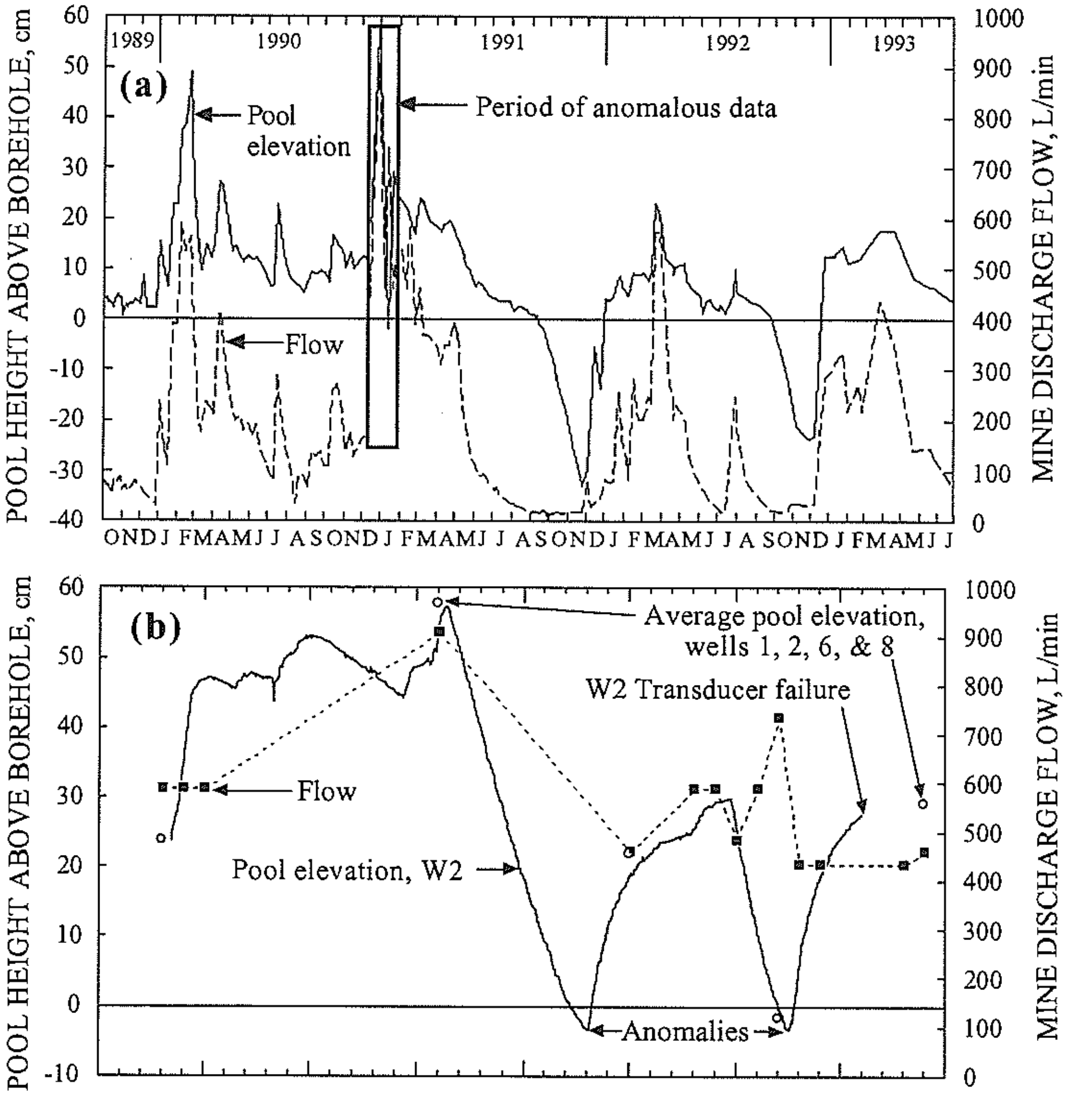

Figure 3. Mine pool elevation and discharge hydrographs:
(a) entire study period; (b) period of anomalous data

The data collected after the breakthrough still appeared to follow a linear pattern (at $h>0$) with a few high, very influential values; however, equation 3 proved to be a very poor predictor of the discharge flow rate. The change resulting from the breakthrough event can be quantified by defining the "conductance" of the mine discharge area as:

$$C_t = Q_t/h \mid h>0 \tag{4}$$

where C is the conductance of the mine discharge area, and the subscript t denotes the parameters of the total mine discharge. If the breakthrough did indeed increase the total conductance of the mine discharge area, the value of this parameter after the breakthrough (C'_t) should be statistically greater than its value before the breakthrough (C_t). Considering that the total flow is the sum of the flows from the borehole (Q_{bh}) and the french drains (Q_{fd}), expressions for the borehole and french drain conductances can be written as:

$$C_t = (Q_{bh} + Q_{fd})/h = C_{bh} + C_{fd}, \text{ where } C_{bh} = Q_{bh}/h \text{ and } C_{fd} = Q_{fd}/h. \tag{5}$$

where the subscripts bh and fd refer to the borehole and french drain flow paths. Before the breakthrough, all the discharge was observed to have come from the borehole, so $C_t = C_{bh}$ and $C_{fd} = 0$ for the pre-breakthrough period. After the breakthrough, the conductance of the flow path to the french drains (C'fd) would increase while that of the borehole (C'_{bh}) would remain unchanged. Therefore, while it would be impossible to quantitatively compare the french drain conductances before and after the breakthrough ($C_{fd} = 0$), the difference between the borehole conductances before and after the breakthrough (C_{bh} and C'_{bh}) should be statistically insignificant.

Direct measurements of the post-breakthrough borehole flow (Q'_{bh}) as required to compute C'_{bh} could not be obtained due to the logistics of the pipe entry to the manhole. However, in November 1992, provisions were made to measure the french drain flows directly, and these were subtracted from the total flows to yield values for Q'_{bh}. The relationship between Q'_{bh} and the total flow Q'_t was almost perfectly linear; the associated Theil regression equation

$$Q'_{bh} = -29.0 + (0.97 * Q'_t) \mid h>0 \tag{6}$$

was used to produce estimates of Q'_{bh} and equation 5 was used to estimate C'_{bh} for most sampling dates (except for dates when $h<0$) between March 1991 and November 1992.

The three conductance groups of interest were C_t (which is also C_{bh}), C'_t, and C'_{bh}; their median values were 1.54, 2.00, and 1.58 m^2/min, respectively, and their distributions were non-normal but similar in shape. To test the significance of the differences between the groups, the rank-sum test (also known as the Mann-Whitney test) was employed. This nonparametric test, first developed by Wilcoxon (1945), determines whether one data set has significantly larger values than another. In each test, a null hypothesis H_o (the values in the two groups do not differ) is compared to an alternative hypothesis H_1 (the values in the groups differ in a specified manner), and a test statistic W_{rs} is computed. The value of W_{rs} determines whether H_o should be rejected in favor of H_1 at a predetermined level of confidence. The test results (table 1) support the hypotheses relating to the breakthrough, i.e., the total conductance of the mine discharge increased significantly while the borehole conductance remained unchanged.

Table 1. Results of rank-sum tests on mine discharge conductances

Null hypothesis H_o	Alternate hypothesis H_1	Test significant at 95% confidence level?	Test statistic W_{rs}	p-value[1]	Interpretation
$C'_t = C_t$	$C'_t > C_t$	Yes	8495	<0.0001	Reject H_o: Total conductance of discharge area increased significantly after breakthrough
$C'_{bh} = C_{bh}$	$C'_{bh} \neq C_{bh}$	No	5409	0.9081	Cannot reject H_o: Borehole conductance did not change significantly after breakthrough
$C'_t = C'_{bh}$	$C'_t > C'_{bh}$	Yes	8403	<0.0001	Reject H_o: After breakthrough, total conductance is significantly greater than borehole conductance

[1] probability that the computed test statistic, or one even less likely, would have been achieved if H_o were true

The final model for predicting the future mine discharge flows from the pool elevation should be based only on data collected after the breakthrough period of January 1991, since these data more accurately represent the discharge conditions that are likely to exist in the future (assuming that no future breakthroughs occur). At positive h values, the total flow, Q'_t (in L/min), can be estimated from the pool height above the borehole, h (cm), by employing the Theil regression equation developed solely from the post-breakthrough data:

$$Q'_t = 20.5 + (22.0 * h) \mid h>0. \tag{7}$$

The borehole flow, Q'_{bh}, can be estimated by using equation 6, and the french drain flow is the difference between Q'_t and Q'_{bh} at the given pool elevation. Figure 4 shows the post-breakthrough data graphically and includes plots of equations 3, 6, and 7 for comparison. The french drain discharge rate (median flow about 30 L/min) did not appear to depend on the pool height at either negative h values, when flow occurred entirely through the french drains (see figure 4), or at positive h values, when borehole flow was dominant. This was attributed to the relatively small pool height fluctuations in comparison to the high resistance (low hydraulic conductivity) of the portal seals and fractured strata which comprised the flow path to the french drains. It is likely that a positive correlation would be found if flow and pool height measurements were made more frequently and accurately and if pool height fluctuations were greater.

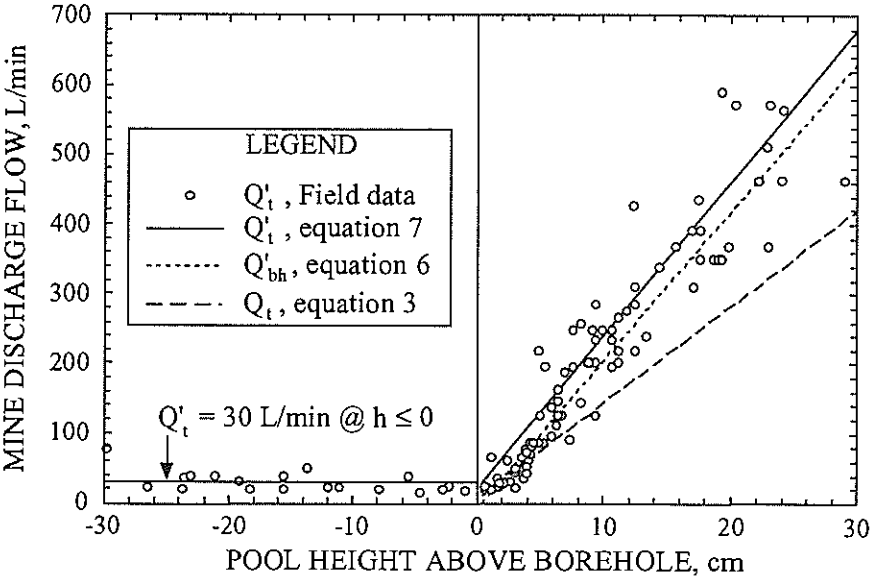

Figure 4. Relationship between mine pool height and discharge, post-breakthrough period

Mine Pool Recharge and Storage Characteristics

Previous reports on this study site (Aljoe, 1992; Aljoe and Hawkins, 1993) provided qualitative evidence that the mine pool recharge was greater in the winter and early spring than in the summer and fall. The availability of mine discharge and pool elevation measurements over a period of more than three years made it possible to quantify the seasonal recharge differences directly, without having to estimate the effects of related parameters such as soil type, soil moisture, and evapotranspiration rate, as would be required in a typical water-balance analysis. The key consideration in the analysis described here is that the change in the volume of water stored in the mine pool (ΔS) is equal to the difference between the total amount of water recharging the pool (ΣR) and the amount discharging from the mine (ΣD) over a given time period:

$$\Delta S = \Sigma R - \Sigma D. \tag{8}$$

If time periods are chosen such that the mine pool elevation (hence storage) is the same at the beginning and end of the time period, then $\Delta S = 0$ and $\Sigma R = \Sigma D$. The mine pool elevation hydrograph of figure 3 was divided into 43 "recharge periods" for which ΔS=0; for each time period, the total discharge ΣD was computed as the area under the mine discharge hydrograph (figure 3), and the recharge ΣR was expressed as a function of precipitation such that

$$\Sigma R = f * A * \Sigma p, \tag{9}$$

where Σp is the sum of the daily precipitation falling on the mine area, A is the mine area over which recharge occurs (approx. 250 acres), and f is the "recharge factor," the fraction of precipitation that reaches the mine pool over the specified period. Recharge factors for each period were obtained by combining equations 8 and 9 and solving for f.

The 43 selected recharge periods ranged from 4 to 54 days in length, and each period was categorized as occurring entirely during one of three "seasons" -- winter (December 21-March 31), spring (April 1-June 30), or summer/fall (July 1-December 20). If recharge is dominated by seasonal effects, there should be significant differences in the recharge factor distributions for different seasons. Figure 5 shows the boxplot representations of the seasonal recharge factor distributions. Although the absolute values of the recharge factors in figure 5 reflect the errors associated with the estimation of ΣD, A, and Σp, these errors do not affect the validity of seasonal comparisons.

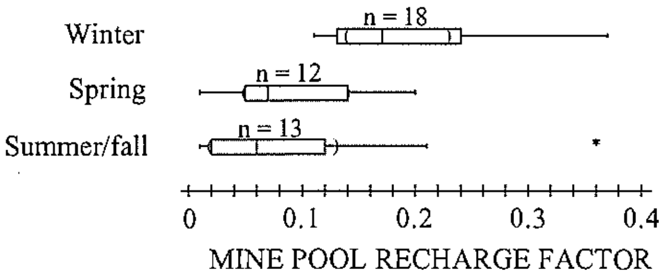

Figure 5. Boxplots of seasonal mine pool recharge factors. The width of each box represents the central 50% of the data; the vertical line within the box is the median; the parentheses represent the 95% confidence interval on the median; the horizontal lines at each end of the box extend to the last data point within 1.5 times the box width from the box end; outliers are denoted with an asterisk; n = number of observations in each group.

Differences between seasonal recharge factors were tested for significance using the rank-sum test, since the recharge factor distributions were found to be nonnormal. Table 2 summarizes the results of the rank-sum tests. As expected, winter recharge was significantly greater than that of the other two seasons; the median recharge factor was about 2.4 times higher (0.17 versus 0.07). However, spring recharge was not significantly different than that of the summer/fall.

Two long periods that were characterized by steady declines and subsequent rises of the mine pool elevation (late summer through early winter of 1991-92 and 1992-93, see figure 3) could not be included in the above analysis because the declines and rises took place during different seasons. For these periods, the change in mine pool storage (ΔS) was estimated by computing the mine void volume associated with the pool elevation change. Equations 8 and 9 were then used to calculate recharge factors for the two "decline" periods, which took place during the summer and fall, and the two "rise" periods, which occurred during the winter. Although the absolute values of the recharge factors were somewhat lower than the median values for the respective seasons (probably because of the error in estimating ΔS), the factors for the two "rise" periods were 2.5 to 3.7 times greater than those of the "decline" periods. This was generally consistent with the seasonal differences in recharge noted above.

Table 2. Results of rank-sum tests on seasonal recharge factors. f_w, f_{sp}, and $f_{su/f}$ represent the recharge factors for winter, spring, and summer/fall, respectively.

Null hypothesis H_o	Alternate hypothesis H_1	Test significant at 95% confidence level?	Test statistic W_{rs}	p-value[1]	Interpretation
$f_w = f_{sp}$	$f_w > f_{sp}$	Yes	359	0.0004	Reject H_o: Winter recharge factor is significantly greater than spring recharge factor
$f_w = f_{su/f}$	$f_w > f_{su/f}$	Yes	370	0.0006	Reject H_o: Winter recharge factor is significantly greater than summer/fall recharge factor
$f_{sp} = f_{su/f}$	$f_{sp} \neq f_{su/f}$	No	167	0.5679	Cannot reject H_o: Recharge factor is not significantly different in spring than in summer/fall

[1] probability that the computed test statistic, or one even less likely, would have been achieved if H_o were true

Water Quality Variations

Mine Void Wells

Figure 1 shows that three of the monitoring wells at the study site (W1, W2 and W6) penetrated the original main entries of the mine, W3 penetrated a submain, and W8 penetrated an isolated room. Aljoe (1992) showed that a significant degree of stratification existed in all five of these wells, i.e., the water sampled near the mine roof was much less contaminated than water at the center or bottom of the entries. This suggested that the flow through all the monitored entries was relatively slow. Comparatively minor differences in AMD contaminant concentrations existed at the bottoms of the voids, suggesting that flow between the monitored entries, if any, was occurring at a level close to the mine floor. It is also possible, however, that flow through the entries was occurring preferentially through other portions of their cross sections, effectively bypassing the portions penetrated by the monitoring wells.

Mine Pillar Wells

All wells in figure 1 except W1, W2, W3, W6, and W8 penetrated solid coal between or adjacent to the mine voids. The five "pillar wells," that were surrounded by mine voids (W4, W5, W7, W9 and W105), had water elevations that were almost identical to those in the voids (Aljoe, 1992), indicating a reasonable degree of hydrologic interconnection. However, AMD contaminant concentrations in the pillars and voids were vastly different. For example, the median concentrations of acidity and sulfate in W4 (613 and 1980 mg/L, respectively) were two to three times higher than those of the voids. Conversely, W7 and W9 were consistently alkaline with very low contaminant concentrations; W5 and W105, while acidic, also had much lower contaminant concentrations than the voids. Geochemical analyses of the drill cuttings obtained from the pillar wells showed no correlation between AMD contaminant concentrations in the wells and the net acid production potential of the overburden immediately above them. Therefore, it appears that the water quality in the pillars is controlled primarily by local geochemical conditions in the immediate vicinity of the wells rather than by the transfer of water from the adjacent voids or the overlying strata.

Water quality in the five wells located in the barrier coal on the downdip side of the mine workings (W101, W102, W103, W104, and W106) also exhibited wide variations, but the differences could be explained more readily by hydrologic considerations. The two wells closest to the mine (W104 and W106) had similar AMD contaminant concentrations (e.g., about 300 mg/L acidity and 1,000 to 1,100 mg/L sulfate). Although the concentrations of some of the AMD contaminants in these two wells were statistically different (rank-sum tests significant at 95% level), they compared more closely to each other than any other two monitoring wells completed in coal. Slug tests in W104 and W106 showed that these two wells had much higher hydraulic conductivities than the other pillar wells. Water quality data collected during pumping tests in these two wells suggested that they were both connected to strong AMD recharge sources, presumably the adjacent mine entries (Aljoe and Hawkins, 1992). Some degree of hydrologic connection with the mine may also exist at W101 and W102, both of which were consistently alkaline but had relatively high concentrations of sulfate and all cations unique to AMD. No such connection appeared to exist at W103, which had circumneutral pH and acidity and very low contaminant concentrations.

Mine Discharge Sources

The most striking and important water quality variations at this site were found at the mine discharge. Table 3 lists the median values of ten AMD-related parameters for the three discharge sources, the mine voids (bottom samples only), and the two "barrier wells" (W104 and W106, see figure 1) which were believed to represent the water quality in the unmonitored set of entries to the northwest of the original mains. Figure 6 shows the boxplot representations of eight of these parameters. For each parameter, significant differences in the median values exist where the 95 % confidence intervals at any two locations do not overlap in figure 6. Note in particular that: (1) most contaminant concentrations were significantly higher in the borehole discharge than in the two french drain discharges; (2) the east french drain discharge had a very high pH and was net alkaline, although its sulfate and AMD-cation concentrations showed that it had undoubtedly come from the mine; (3) the west french drain discharge was similar to the borehole discharge in sulfate concentration but had a higher pH and significantly less acidity, iron, and aluminum; (4) the borehole and west french drain discharges were generally more contaminated than the monitored mine voids; (5) the borehole discharge quality was similar to that of W104 and W106; (6) the calcium concentrations were higher in the two french drains than in the other locations; and (7) the concentrations of three relatively "conservative" AMD ions -- sulfate, magnesium, and sodium -- were about the same in the mine voids as in the east french drain.

Table 3. Median AMD-related water quality parameters in mine pool and discharge.

Parameter	Borehole Discharge	East French Drain	West French Drain	Wells 104 and 106	Voids (Bottom)
Number of Samples	141	56	57	20	84
pH	3.11	6.37	3.99	3.03	3.31
Net Acidity	365	-45.5	208	303	187
Total Iron	93.8	28.9	69.4	104.5	60.3
% Ferrous	72.3	99.0	100.0	97.9	97.1
Sulfate	1125	868	1074	1025	840
Calcium	185	248	224	184	162
Magnesium	74.4	56.6	69.5	70.4	53.8
Sodium	7.5	13.5	8.2	6.6	13.1
Aluminum	18.9	3.7	12.6	15.9	9.6
Manganese	13.6	12.7	12.8	13.4	5.9

pH in standard units; % Ferrous in percent; all other data in mg/L

These water quality patterns suggest that there are two largely independent internal flow paths within the mine pool. The set of entries near W104 and W106 constitutes the primary flow path; this path discharges mostly through the borehole, which is located where the flow path intersects the west main entry. This would explain the similarities in water quality noted in (5) above. The original main entries of the mine, in which the portal seals were constructed, constitute a secondary flow path whose water quality is represented by the void wells. A portion of the primary flow path mixes with the secondary path in the west main entry, and the mix is chemically altered as it passes through the portal seals to the french drains. A report on the mine sealing project (Chung, 1973) shows that the seals contained large amounts of limestone aggregate and cement grout, which would account for the higher calcium concentrations in the french drain discharges. The west french drain represents the preferred flow path through the portal seals; its flow rate was consistently four times higher, its AMD contamination was much greater, and its calcium concentration was significantly lower than those of the east french drain. During periods of high pool elevation, diffuse seepage of AMD emanated from the ground immediately above and adjacent to the west french drain. These characteristics suggest that the west portal seal and the surrounding strata are more heavily fractured than elsewhere in the discharge area. Note also (figure 1) that the west portal seal is situated at the structural low point of the mine, and would therefore be subject to greater hydrostatic pressure than the other portal seals. The high degree of neutralization evidenced in the east french drain is the result of very slow seepage through the portal seals. Because of its location and the chemical similarities noted in (7) above, the east french drain probably derives most of its discharge from the secondary internal flow path.

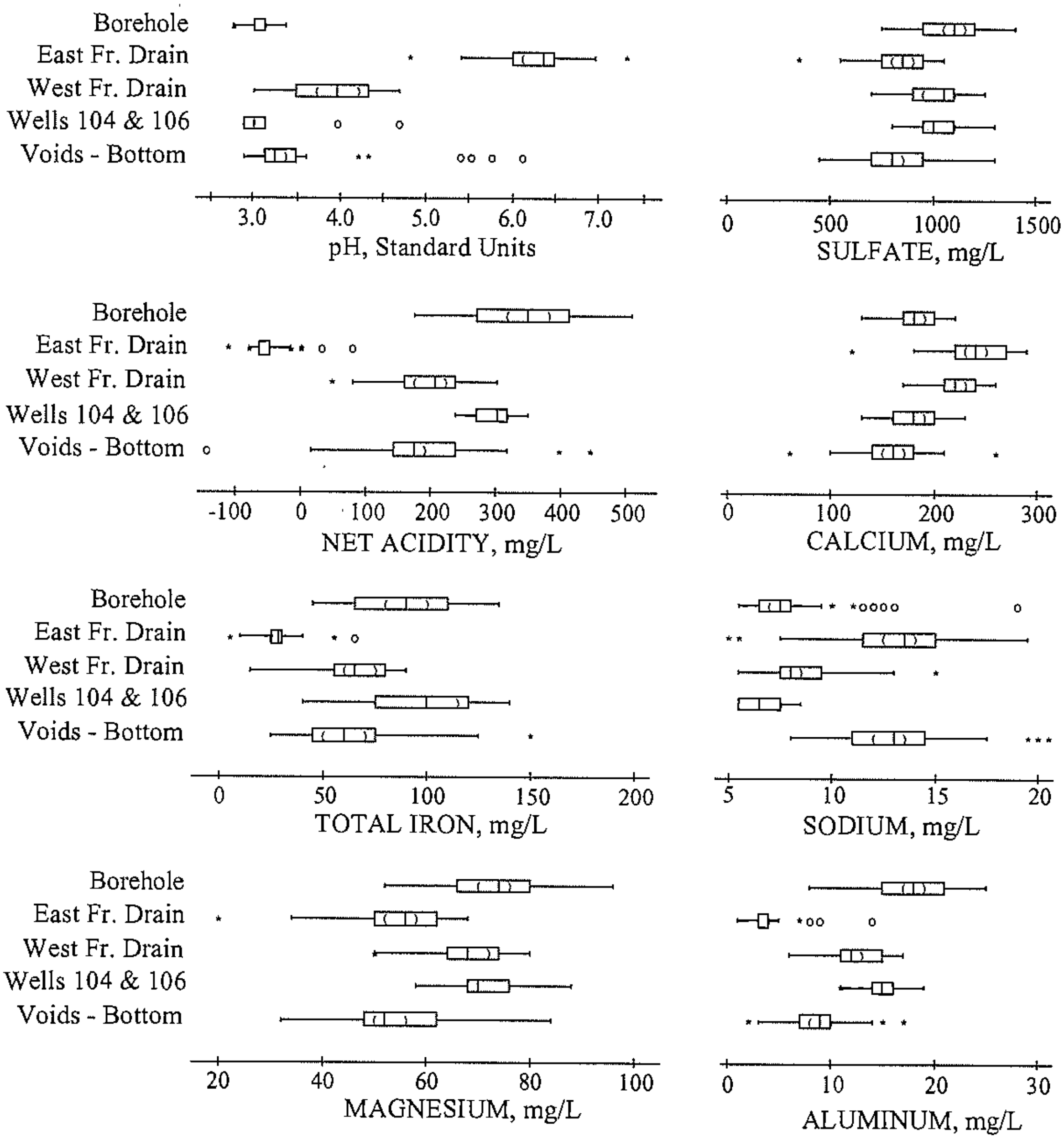

Figure 6. Boxplots of mine pool and discharge water quality parameters. See figure 5 for explanation of symbols; medians and confidence intervals are not shown when they coincide with the box ends; circles denote extreme outliers.

Tracer Tests

Aljoe and Hawkins (1992) described the results of a bromide tracer test, using W6 for tracer injection, which confirmed the hydrologic connection between the original main entries and the french drains. 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, remained relatively constant (close to 1.0 mg/L) through the 54th day, and continued at just above the detection limit (0.1 mg/L) for almost a year after tracer injection. This suggested a slower flow path to the east french drain, with greater opportunity for chemical change. Bromide concentrations in the borehole discharge were negligible. Tracer migration away from the injection well was more than three times as rapid at the bottom than at the top of the mine void, supporting the earlier inference of a higher flow rate along the mine floor.

Discussion and Conclusions

For mine pools with reasonably well-defined "spillover points" (e.g., boreholes or open fractures), the pool elevation can provide a reasonable estimate of the mine discharge rate. This can be an advantage in long-term monitoring because of the lower maintenance costs associated with pool elevation measurements. While the functional relationship between elevation and flow is linear, the predictive equation should be generated by non-parametric rather than parametric regression techniques in order to reduce the influence of high outliers. Data on both parameters should be collected for several water years before relying on pool elevation as a predictor, and discharge conditions should be field-checked periodically. This is especially important during high-pool periods, which can create or enhance discharge paths other than the one for which the predictive equation was developed. If this occurs, a new round of data collection for all discharges will be necessary, and new predictive equation(s) must be generated.

The efficiency of recharge to the mine pool, as defined by the "recharge factor" (recharge per unit precipitation input) was generally more than twice as high during the winter months compared to the rest of the year. This can be attributed primarily to the low temperatures and lack of plant activity during the winter, which combine to reduce evapotranspiration. In addition, snowmelt represents a gradual, widespread application of water to the land surface, which would tend to favor recharge versus runoff. Conversely, intense spring and summer rainstorms would tend to favor runoff over recharge. The lack of significant differences in recharge during the spring, summer, and fall can be explained by the offsetting effects of plant activity and temperature. During the spring, plant activities are relatively high while temperatures are low; during the summer and fall the reverse is true. Also, the accumulated effects of warm temperatures and plant activity create an undersaturated condition in the soil and overburden in the summer and fall. This moisture demand must be met before accelerated recharge to the mine can begin. This demand was apparently met on at least one occasion during the summer/fall period (outlier in figure 5); this event occurred at the end of a long period (1-2 weeks) of cool temperatures and consistent, heavy rainfall.

The wide variations in water quality that existed among the mine voids, pillars, and discharges can be attributed to several hydrologic and geochemical factors. Water quality in mine voids was vertically stratified, indicating a relatively slow flow velocity at the monitoring points. The vast differences in pillar water quality could not be explained by vertical or lateral flow from adjacent overburden or voids, and it was postulated that local pillar geochemistry was responsible. However, water quality patterns in four of the five wells in the barrier pillar immediately downgradient of the mine could be related to recharge from the adjacent voids. Differences in water quality at the three mine discharge points were attributed to the partial mixing of two internal flow paths through the mine prior to discharge, coupled with varying degrees of chemical alteration upon seepage through the calcareous portal seal materials. The apparent complexity of the internal flow and discharge patterns was somewhat surprising, given the close proximity of the discharges to each other and the relative simplicity of the deep mine itself (only a few open mine entries with no evidence of collapse). This implies that multiple flow paths will exist at any flooded deep mine, and a comprehensive definition of these paths would be necessary prior to implementing any type of in situ AMD treatment scheme. Conversely, the apparent existence of "natural" AMD amelioration at the east french drain provides encouragement that in situ treatment may be possible at the study mine if the neutralizing agents can be introduced along the primary flow path. Efforts are currently underway to develop a passive AMD treatment scheme that takes advantage of the observed hydrologic and geochemical characteristics of the mine pool.

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