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STATISTICAL CHARACTERISTICS OF COAL-MINE DISCHARGES ON WESTERN PENNSYLVANIA REMINING SITES[1]

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ABSTRACT: Under an approved remining program, a coal mine operator can remine abandoned sites without legally assuming treatment responsibilities of the previously degraded water, as long as these discharging waters are not further degraded. Determination of discharge degradation caused by remining of abandoned coal mines requires knowledge of mine water quality and discharge flow rate characteristics both before and after remining. Normality tests performed on the water quality and flow data from 57 mine discharges indicate generally nonnormal distributions and extreme right-skewness. Exploratory data analysis (notched box-and-whisker plots) of the differences among medians indicates that the water quality of underground mines was more highly degraded in terms of acidity, iron, and sulfate concentrations than that from surface mines. Spearman's rank correlation tests, normality testing, and exploratory data analysis indicate that discharge flow rate is the primary controlling factor on the variability of pollution load rate. Reduction of recharge from the surface and adjacent unmined strata should decrease the mine discharge flow rate and in turn the pollution load.
(KEY TERMS: remining; pollution load; normality tests; exploratory data analysis; correlation analysis; water quality.)

INTRODUCTION

Remining, in the eastern U.S. coal fields, is generally defined as surface mining of previously mined and abandoned surface and/or underground mines that created and continue to possess mine drainage discharges that fail to meet applicable effluent standards (Pennsylvania Bulletin, 1985). Under an approved remining program, a mine operator can remine these sites without legally assuming treatment liabilities of the previously degraded water, as long as these discharging waters are not further degraded. If the mine water is additionally degraded because of remining, treatment is based on mine site background pollution load levels, and not legislatively mandated effluent standards.

In Pennsylvania, pre-remining water-quality data are used as background to determine if additional degradation has occurred as a result of remining. Prior to remining, the mine operator collects and chemically analyzes a series of mine discharge water samples and determines the flow rates. Pre-remining pollution baseline loading rates (in kilograms or pounds of pollutant per day) are established with these data. These data are submitted as part of the remining permit application. The final baseline loading rates are also subject to the strength of the pollution abatement plan and the economics of conventional treatment. Statistical analyses, primarily exploratory data analysis (schematic summary), are used to ascertain if the post-remining discharges have been degraded relative to pre-remining conditions (Pennsylvania Department of Environmental Resources *et al.*, 1988). If the pollutant loads are below limits based on pre-remining pollutant loads, the remining operator is released of liability at the completion of other reclamation requirements.

To adequately evaluate the effectiveness of remining, a basic understanding of the water-quality and flow-rate characteristics is required. Success of a remining operation is defined primarily by the lack of additional mine-water pollution (technically, a decrease in the pollution load) and by the reclamation of abandoned mine lands. The amount of reclamation achieved by the operation is easily quantifiable in terms of abandoned mine hectares regraded, linear meters of highwall eliminated, or hectares of underground mines daylighted (surface mining of the remaining coal by the removal of the overburden).

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The determination of changes in water quality and/or flow rate is, on the other hand, much more difficult to quantify. In order to accurately ascertain changes caused by remining, trends and characteristics of the pre- and post-remining water quality and flow rates must be evaluated in an unbiased manner. Specifically, there is a need to characterize discharge water quality and flow, and to evaluate different statistical testing procedures for analyzing the effects.

My goal in writing this paper is to provide characteristics of hydrologic data from acid-producing coal mines using normality testing (skewness and chi-square), exploratory data analyses (notched box-and-whisker plots), and ranked correlation coefficient determinations (Spearman's rank correlation). There are other applicable testing techniques available, including but not limited to seasonality and serial dependence tests. These may be explored in the future.

Previous Research

Smith (1988) analyzed the effects of seasonal variations on pre-remining flow rates, acidity concentrations, and acidity loads of three mine discharges in Pennsylvania. The discharges were located in three different hydrogeologic settings and exhibited distinctly different characteristics. Discharge characteristics were categorized as (1) high flow-low concentration/low flow-high concentration, (2) steady or damped response, and (3) "slugger" (discharge flow increases were not accompanied by changes in acidity concentration). Discharge flow rate was observed to dominate the acidity loading determinations; therefore, a strong positive correlation between flow and load was anticipated. The research indicated that sampling to determine pollution loading rates should be at a duration and consistent frequency to accurately characterize both high and low flow periods of a discharge, not overemphasizing any one period (Smith, 1988).

Helsel (1983) analyzed streams from mined and unmined watersheds in eastern Ohio to determine the influence of mine and rock type on water quality. He determined that overburden lithology influenced several water quality constituents. The water quality exhibited neither a normal nor lognormal distribution. The effects of mine and rock type on water quality were more adequately shown using analysis of the ranked data, rather than analysis of the actual data.

Previous research has indicated that under many nonmining related circumstances, hydrologic data are generally nonnormally distributed (Berryman *et al.*, 1988). Researchers have observed that water quality data tend to be asymmetric and skewed right (Hirsch and Slack, 1984; Montgomery *et al.*, 1987). Given these nonnormal tendencies, the use of parametric statistics which are sensitive to assumptions of normality may lead to erroneous determinations of degradation or nondegradation. Montgomery *et al.* (1987) and Helsel (1987) suggested the use of nonparametric statistical methods for nonnormally distributed data or performing some form of data transformation to approximate a normal distribution prior to statistical analyses. Logarithmic transformation will commonly eliminate skewness and asymmetry, transforming these data into an approximate normal distribution (Harris *et al.*, 1987; Norcliffe, 1977).

Of the numerous statistical methods for determining data normality, Harris *et al.* (1987) considered the skewness test to be the best for ground-water quality parameters and the chi-square goodness of fit not to work as well. However, when the sample size is small (under 24), all of the tests for the assumption of normality begin to lose statistical validity (Montgomery *et al.*, 1987).

Background

This paper presents the results of univariate and bivariate statistical analyses of data from 57 mine discharges emanating from coal remining operations in the bituminous coal fields in western Pennsylvania. The data for this study were obtained from 24 surface mining (remining) permits of the Pennsylvania Department of Environmental Resources (PADER). These 24 remining operations (see Figure 1) were selected from a larger group of 105 potential sites. The permits that were selected possessed sufficient post-remining hydrologic data (a minimum of one year, dating from rough backfilling) to permit comparison with the pre-remining data.

The hydrologic data obtained from the remining permits include pH, acidity, total iron, total manganese, total aluminum, sulfate, and flow rate. However, only acidity, total iron, sulfate, and flow rate will be discussed here. Under present Pennsylvania remining regulations, acidity and iron loading rate effluent standards are required for all permits regardless of the concentration of each parameter with respect to the legislatively mandated effluent standards. Sulfate is analyzed in this paper because it serves as a conservative indicator of acid mine drainage (AMD) production and can be used to evaluate changes in discharge quality. Increased sulfate concentration, in the Appalachian coal mining region, is generally indicative of acid production by iron-sulfide oxidation.

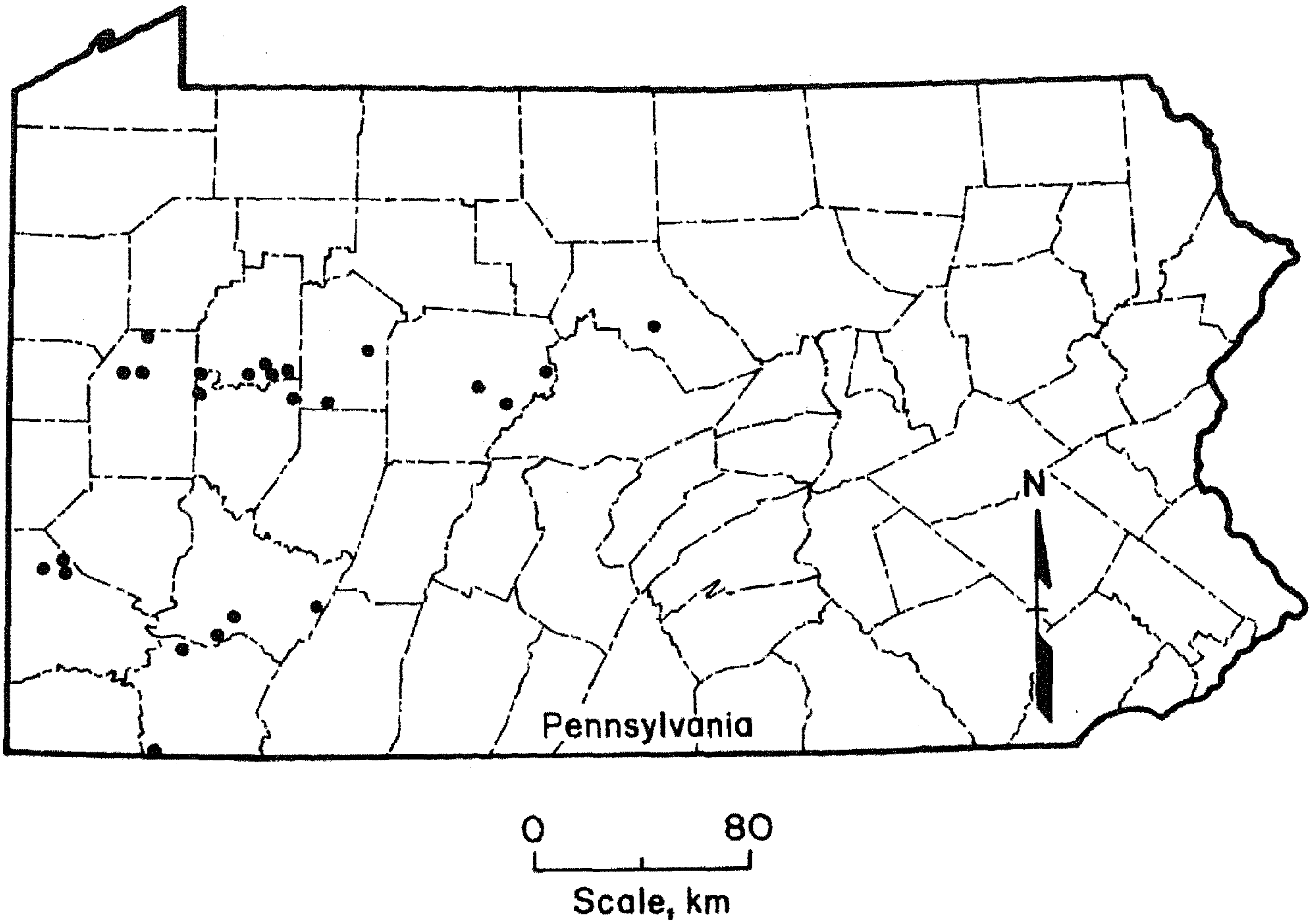

Figure 1. Location Map of the 24 Study Sites.

In this process, the sulfate ion (SO_4^{-2}) is released into solution. Discharge flow rate is needed along with concentration to calculate pollutant loads.

Acid mine drainage is created when metal sulfide minerals (usually pyrite) oxidize and the oxidation products are mobilized. Ground water serves as the transport medium of the oxidation products. Recharge events tend to "flush out" the oxidation products as the wetting front moves through the unsaturated portion of the spoil. When coal is surface mined, the overburden material is broken up into particles with sizes ranging from clay (< 0.002 mm) to boulder (> 256 mm). This overburden rock fragmentation greatly increases the rock surface area, thus exposing additional pyritic minerals to oxidation from atmospheric oxygen and iron-oxidizing bacteria. This promotes a state of geochemical flux for a period of time after mining. Based on subsidence observations and aquifer testing, mine spoil continues to undergo considerable physical changes caused by compaction, shifting, and piping by ground water for at least 30 months after reclamation (Aljoe and Hawkins, 1992). Spoil continues to physically change well beyond 30 months after reclamation, but at a reduced rate. All of these physical processes directly affect the hydraulic properties of the spoil aquifer.

The number of mine discharges sampled at each of the 24 sites ranged from one to five, totalling 57. Pollutant concentrations were reported in milligrams per liter (mg/L). Flow was reported in gallons per minute (gpm). The data were transformed into units of pounds of pollutant per day (lbs/day), which are the units of effluent baseline pollution load, used in Pennsylvania for remining permits. Load was subsequently converted to kilograms per day. The pre- and post-remining data were analyzed as separate data sets because of significant physical and geochemical changes that can occur to the mine spoil aquifer during mining and subsequent reclamation. The pre-remining sampling period ranged from 3 to 42 months with the collection of 3 to 38 samples. All but two sites had at least six pre-remining samples. The average pre-remining sample set contained 17 samples. The post-remining sampling period ranged from 12 to 65 months with 7 to 71 samples collected with an average of 30 samples. Table 1 summarizes the median concentrations and flow rates for the 24 sites. For portions of the statistical analyses, the data were further differentiated into underground mine and surface mine discharges to ascertain potential differences between pre- and post-remining data.

TESTS FOR NORMALITY

Discharge flow rate, contaminant concentration, and loading rate data before and after remining were tested for normality by using the skewness test and the chi-square goodness-of-fit test. The results of these analyses are summarized in Table 2. The data were tested for normality at the 5 percent significance level and form of skewness (left or right) was determined. The skewness test was conducted as described by Harris *et al.* (1987) and Snedecor and Cochran (1971). The chi-square "goodness-of-fit" test procedure was performed as described by Davis (1986).

Skewness Test

The skewness testing indicates that the flow rate, concentration, and loading rate data are generally nonnormally distributed at the 5 percent significance level. The major exception is the sulfate concentration. The nonnormally distributed data for sulfate concentration slightly outnumber those that are normally distributed for both pre- and post-remining periods. For other parameters, nonnormally distributed data exceed the normally distributed data sets by at least a two to one margin. In total, the distribution of pre-remining variables are 277 nonnormal compared to 112 normal. The margin of the post-remining total is slightly less, 272 to 117. The dominating influence of flow on the loading rate is indicated by the differences between the pre- and post-remining distribution of sulfate concentrations and sulfate loads. Sulfate loads are similar to the corresponding flow and dissimilar to the distribution for the sulfate concentrations. This indicates that the flow influence

TABLE 1. Summary of Remining Data.
All data are median values, except n which is the number of samples.

Site	Pre-Mining					Post-Mining				
	n	Flow L/m	Acid mg/L	Fe mg/L	SO_4 mg/L	n	Flow L/m	Acid mg/L	Fe mg/L	SO_4 mg/L
1	17	8	19	0.2	339	13	4	30	0.2	420
2	21	1181	321	24.1	814	41	1283	261	20.5	852
3	22	23	511	62.0	1132	14	4	512	36.0	1089
4	10	144	43	2.9	92	45	155	162	21.9	602
5	38	193	18	0.1	151	19	182	11	0.1	118
6	21	110	143	2.7	732	16	140	128	2.3	722
7	31	469	1020	11.3	1077	11	466	850	12.8	1087
8	10	204	777	99.3	1695	40	117	294	37.6	2189
9	4	261	1447	58.1	2671	16	95	742	54.7	2230
10	9	250	4	0.6	53	33	144	3	0.5	51
11	6	280	302	10.9	991	17	38	262	6.7	882
12	12	462	58	0.2	NA	63	140	23	0.4	326
13	11	53	5	0.2	NA	56	30	10	0.2	649
14	28	11	9	1.2	159	46	15	9	0.8	204
15	9	19	136	3.5	236	24	8	299	1.6	876
16	3	189	456	295.0	1430	71	148	541	218.5	1202
17	26	64	80	1.0	515	43	45	2	1.7	690
18	24	265	2	0.4	153	33	348	10	0.3	270
19	18	34	16	0.2	74	36	42	83	1.1	446
20	8	140	208	3.3	740	7	4	19	0.5	749
21	16	42	90	2.5	231	21	61	90	2.6	379
22	28	238	231	4.8	931	10	428	151	5.9	779
23	8	344	89	4.6	253	25	220	127	9.8	374
24	18	11	566	64.1	673	12	0	677	176.8	1816

TABLE 2. Summary of Results of Tests of Normality. A P value greater than 0.05 indicates the data were not normally distributed at the 5 percent significance level; a P value less than 0.05 indicates that the assumption of normality cannot be rejected with greater than 95 percent confidence. NA signifies that there were insufficient degrees of freedom to adequately conduct the chi-square test.

	Skewness Test		Skewness		Chi-Square Test		
	P>0.05	P<0.05	Left	Right	P>0.05	P<0.05	NA
Pre-Remining							
Flow Rate	45	12	12	45	12	1	44
Acid Concentration	35	22	22	35	4	7	46
Acid Load	42	15	8	49	9	2	46
Fe Concentration	40	17	11	46	6	4	47
Fe Load	45	12	10	47	10	4	43
SO_4 Concentration	28	24	22	30	4	8	40
SO_4 Load	42	10	12	40	11	1	40
Post-Remining							
Flow Rate	41	16	7	50	21	7	29
Acid Concentration	35	22	13	43	21	6	30
Acid Load	40	17	3	54	24	5	28
Fe Concentration	52	5	6	51	17	8	31
Fe Load	42	15	5	52	25	4	28
SO_4 Concentration	27	25	15	37	12	12	28
SO_4 Load	35	17	2	50	15	8	29

on load overrides the sulfate concentration influence. This strong influence of flow on load determination is important information for the implementation of abatement techniques intended to reduce the pollution load.

The overwhelming majority of the pre- and post-remining data sets, 629 out of 777 (see Table 2), tend to be skewed right (toward lower values). These trends are similar to those observed by Montgomery *et al.* (1987) for ground-water quality. The ratio of right to left skewed data ranges from a low of approximately 1.4 to 1 for pre-remining sulfate concentration to a high of 25 to 1 for post-remining sulfate load. In general, the number of concentration data sets skewed right for the post-remining period exceeds that for the pre-remining period. Skewness of the loading data sets is more predominately to the right than either the flow rate or the concentration data sets. This increase in skewness appears to be caused by the interdependence of concentration to flow (e.g., concentration increases caused by "flushing and concentration decreases caused by dilution).

Chi-Square Test

Table 2 indicates that the chi-square test produces results similar to the skewness tests, but because of its nonapplicability, a direct comparison cannot be performed. The chi-square test results illustrate that the majority of the flow, concentration, and loading rate data are nonnormally distributed at the 5 percent significance level. However, there are some inconsistencies within the pollutant concentration data sets before and after remining.

Chi-square testing of the pre-remining pollutant concentration data sets indicates that they are more commonly normally than nonnormally distributed by a margin of 19 to 14. Conversely, the post-remining data tend to be more often nonnormally distributed than pre-remining (50 to 26). These differences between pre- and post-remining concentration data may be related to the limited number of tests that could be adequately conducted compared to the skewness tests.

The chi-square testing indicates that the pollutant loads exhibit similar distributions as the corresponding flow data. This suggests that flow rate is the most dominant influence on loading rates, as also observed by Smith (1988) for acidity. This is especially evident with chi-square tests for the pre-remining acidity and sulfate. These concentrations exhibit mainly normally distributed data sets, while the chi-square tests on the corresponding loading data sets indicate that they are mostly nonnormal at the 5 percent level, mirroring the trends of the flow data sets. If surface recharge and ground water flow into and through these mine sites can be controlled, the mine operator may be able to engineer a reduction in discharge outflow and in turn pollution load during mining or reclamation.

EXPLORATORY DATA ANALYSIS

One tool of exploratory data analysis is the "notched box-and-whisker" plot. This type of plot is used to graphically display several basic statistical parameters. These plots are useful for comparison of subsets of data (Figures 2-5). These notched box-and-whisker plots were developed as described by McGill *et al.* (1978).

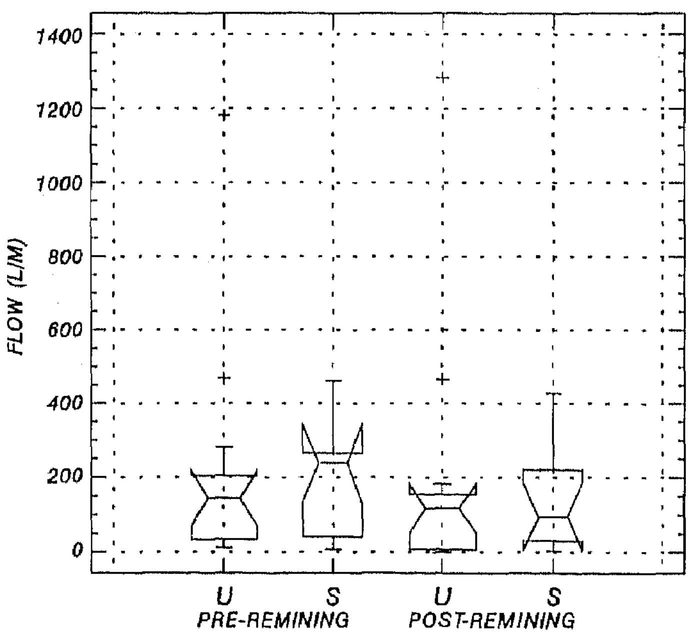

Figure 2. Plot of the Median Flow Rate Measurements of Underground (U) and Surface (S) Mines Before and After Mining.

Figure 2 is a notched box-and-whisker plot representing the sum of the median flow rate measurements for each site classified by mine type (underground and surface) before and after remining, respectively. The comparison of surface and underground mine discharge flow rate characteristics before and after remining indicates that there is no significant difference (at the 95 percent confidence level) of the median values.

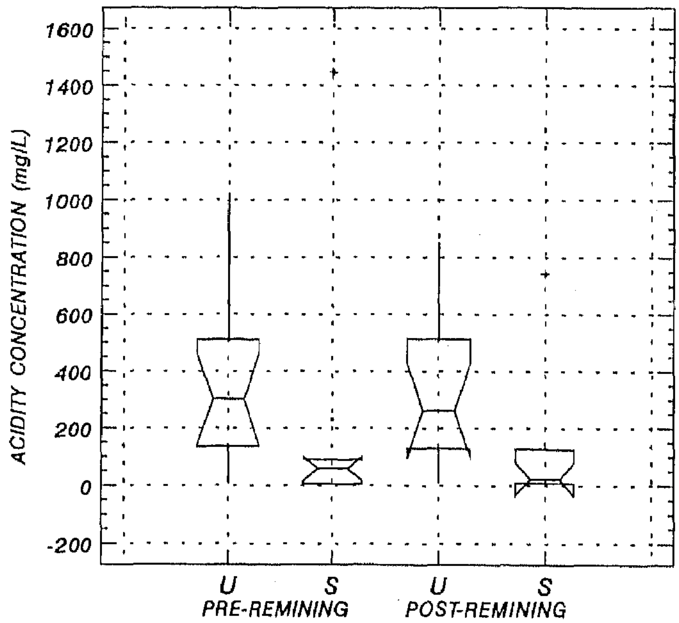

Figure 3. Plot of the Acidity Concentration Medians of Underground (U) and Surface (S) Mines Before and After Remining.

Figure 3 exhibits the mine average acidity concentration determined from the individual discharge median values. Figure 3 illustrates that the pre- and post-remining median of the acidity concentrations for underground mines is significantly higher than the acidity concentrations for surface mines. The reason for higher acidity values in the underground mines is that ground water flows mainly through the portions of the mine where pyrite is exposed and AMD forms (relatively high sulfur coal, seat, and roof rock). Conversely, Hawkins and Aljoe (1991) observed that in surface mines, ground water flows along relatively discrete paths in the highly fragmented, poorly sorted spoil material. Portions of the spoil may consist mainly of acid-forming materials (e.g., high-sulfur black shales, sandstones, and spoiled coal), while other parts may consist mainly of alkaline materials (e.g., limestones and carbonate-rich shales). The underground mine discharges generally exhibit a broader range of values, excluding the outliers and far outliers, than the surface mine discharges (Figure 3).

The broad range of acidity concentration exhibited by the underground mines may be caused by a broad range of site ages. The abandoned underground mines may be up to, and in a few cases exceeding, 70 years old. In the older sites, natural amelioration of the AMD-forming mechanisms over time may permit lower acidity values as the exposed pyritic minerals are exhausted. Relatively newer underground mines, in the same coal seams and in the same region, may yet yield elevated acidity concentrations. Similar natural amelioration was observed by O'Steen and Rauch (1983) at surface mines in northern West Virginia. Natural amelioration processes have had less time to reduce the severity of discharges from abandoned surface mines because most are under 20 years old. In Figure 3, post-remining acidity concentration is nearly identical to the pre-remining plot, indicating that little change occurred relative to the abandoned mine type.

Figure 4, a plot of the average iron concentration, is similar to the acidity concentrations (Figure 3), although the data ranges are narrower. However, the differences between any of the medians are not significant at the 95 percent level. These trends observed for iron concentrations are related to the same causal factors as those described for acidity.

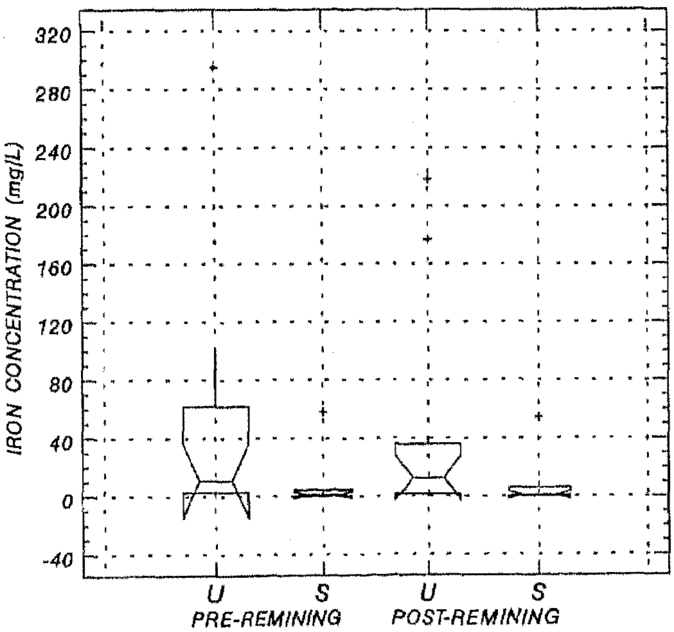

Figure 4. Plot of the Iron Concentration Medians of Underground (U) and Surface (S) Mines Before and After Remining.

Figure 5, the plot of the average sulfate concentration medians, is similar to those of acidity and iron. In general, the underground mine median value is higher and the interquartile range is broader than that of surface mines. The pre-remining medians are not significantly different at the 95 percent level. However, the post-remining sulfate values exhibit a significant difference at the 95 percent level. This is caused by a rise in the underground mine median and a narrowing of the approximate 95 percent confidence interval about the median (notches) of the underground mine data, which indicates that daylighting underground mines may cause an increase in their AMD production and greatly reduce the variability of sulfate concentration.

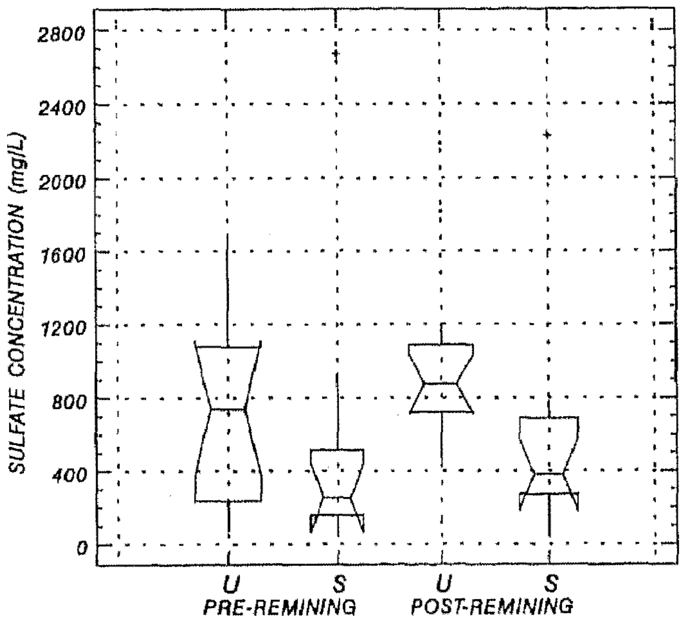

Figure 5. Plot of the Sulfate Concentration Medians of Underground (U) and Surface (S) Mines Before and After Mining.

Load plots (not shown) were created for acidity, iron, and sulfate for underground and surface mines. The configuration of these plots is similar to those of the corresponding concentration plot, indicating that concentration does influence load. However, none of the loadings differed significantly at the 95 percent level. This mirrors the flow plot (Figure 1), which did not exhibit significant differences. This indicates that flow rate may have a stronger influence on loading than concentration.

NONPARAMETRIC CORRELATION

Spearman's rank correlation was performed as described by Davis (1986). For the purposes of this study, critical values of Spearman's rank correlations were examined at P = 0.05.

Spearman's rank correlation coefficient was used to determine the interrelationship that flow and concentration have on the loading rate. The results, summarized in Table 3, illustrate that flow is more commonly correlated to the pollution load than the pollutant concentration.

TABLE 3. Summary of Significant Correlations Using Spearman's Rank Correlation. The values are the number of data sets exhibiting a significant positive (+) and negative (–) correlation at the P = 0.05 level.

	Pre-Remining			Post-Remining		
	Acid	Fe	SO_4	Acid	Fe	SO_4
Flow (+) vs Load (–)	42	29	37	51	42	51
	0	0	0	0	0	0
Concentration (+) vs Load (–)	10	14	8	30	30	12
	5	5	4	7	2	6

Approximately 82 percent (93 of 114) of the acidity loadings are significantly correlated to the flow rate, while concentration exhibits a significant correlation to load for about half (52 of 114) of the cases. The flow rate correlations are in all cases positive, indicating that flow increases are accompanied by load increases. Significant correlations of flow to acidity load increased moderately from pre- to post-remining. Preremining acid concentration exhibits a positive correlation to pollution load about one fourth as often as flow. Post-remining acidity concentration was correlated positively to load three times as often as preremining. Iron and sulfate correlations exhibited similar results as acidity. However, iron exhibited the weakest flow rate to pollutant load correlation of the three contaminants.

Overall, significant positive correlations of flow rate versus loading outnumber concentration versus loading by over 2 to 1 (252 to 104). The increase of the post-remining positive correlation of flow rate and concentration to load may be related to the state of geochemical and physical flux of mine spoil during this period. The water table is in the process of rebounding (reestablishing) while the spoil is undergoing considerable changes that directly affect the transmissive properties of the aquifer. High recharge events will tend to "flush out" high levels of contaminants from the freshly exposed and oxidized pyrite, while also yielding higher flow rates. The Spearman rank correlations indicate, as the normality tests and the notched box-and-whisker plots did, that for determination of pollution loading rates, flow rate is the main controlling factor.

All negative correlations were exhibited by contaminant concentration to load. This may be caused by dilution of contaminants from increased flow rates; also, in the cases of acidity and iron, geochemical changes of the ground water may reduce concentrations through chemical reactions. During high flow events the sources and flow paths of the ground water may change, thus facilitating water quality changes. Chemical reactions, brought on by ground water quality changes, can reduce the acidity and iron content, but generally will not affect the sulfate content (at the levels of sulfate observed). The number of negative sulfate concentration to load correlations was similar to iron and acidity, indicating that dilution and not chemical reactions may be the main cause of most negative correlations.

SUMMARY AND RECOMMENDATIONS

To accurately assess the success of remining in reducing discharge pollution loads, a basic understanding of the statistical characteristics of the hydrologic data is required. With an understanding of mine discharge water quality and flow rate characteristics, the proper statistical methods can be applied to determine changes caused by the remining operation. To determine characteristics of hydrologic data from coal mines, the data were analyzed using several statistical techniques.

Testing for normal distribution using the skewness and chi-square tests indicates that water quality and flow rate data tend to be nonnormally distributed. Remining appears to increase the tendency of these data to be nonnormally distributed, especially during the first few years after reclamation. The hydrologic data are commonly skewed to the right. Trends exhibited by the normality tests indicate that flow is the dominant factor for determining the pollution load rate.

The notched box-and-whisker plots indicate that underground mine discharges tend to be more severely degraded in terms of pollutant concentration than those from surface mines in the remining data set. This is caused in part by differences in the ground water flow regime of the two mine types. There is also a strong influence of flow rate on the pollutant load, although concentration is not entirely insignificant in influencing the pollutant load.

Spearman's rank correlation testing illustrates that flow rate is more commonly strongly correlated to pollution load than concentration. This indicates that flow rate is the main determining factor for pollution load.

If the discharge rate can be reduced by mining or reclamation practices, the mine operator may be able to virtually guarantee a reduction of the pollution load. A flow reduction may be achieved by diversion or exclusion of ground water from adjacent areas from the spoil and/or reduction of surface infiltration. Methods for ground water diversion or exclusion include but are not limited to drains or grout curtains at the final highwall, sealing of exposed underground mine entries, and/or pumping of dewatering wells in adjacent areas. Reduction of surface infiltration can be achieved by diversion of surface water away from mined areas, regrading the site with sufficient slope to promote runoff, revegetation, elimination of surface impoundments, and installation of a low permeability cap (using natural or manmade materials) over the mined areas to reduce recharge from precipitation.

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