Effectiveness of Pennsylvania's remining program in abating abandoned mine drainage: water quality impacts

M.W. Smith
District mining manager, Pennsylvania Department of Environmental Protection, Hawk Run, Pennsylvania

K.B.C. Brady
Hydrogeologist, Pennsylvania Department of Environmental Protection, Harrisburg, Pennsylvania

J.W. Hawkins
Hydrogeologist, OSMRE, Pittsburgh, Pennsylvania

Abstract
The Pennsylvania Department of Environmental Protection (PaDEP) has been issuing surface mining permits since 1984 that authorize remining in areas that will affect preexisting pollutional discharges. These permits require the mine operator to employ best management practices to reduce pollution loading from abandoned mine discharges. A total of 110 completed mining operations with 233 discharges were evaluated to determine the impact to water quality. Overall, acid loading from these discharges was reduced by 7,200 kg (15,900 lbs) per day or 61%. Metal loadings were also reduced. For acidity, 49% of discharges improved or were eliminated, 52% showed no significant change and fewer than 1% got worse. Loading reductions resulted from a combination of reduced concentrations and lower flows.

Introduction
This paper reports on the effectiveness of remining abandoned coal mines to reduce the pollution load of preexisting mine-drainage discharges. Remining is defined herein as the surface mining and reclamation of abandoned surface and underground mines with the intent of improving the water quality of preexisting acidic and/or metal-laden discharges, extracting the remaining economically minable coal reserves and performing additional reclamation. Improvement of the discharges is primarily achieved by implementation of best management practices (BMPs) during mining and/or reclamation. BMPs, as they relate to remining of abandoned coal mines, are a variety of mining and reclamation procedures, techniques and practices that when properly employed will:

- cause a decrease in the pollution load by reducing the discharge rate and/or the concentration of the pollutant,
- reduce erosion and sedimentation control problems and/or
- result in improved reclamation and revegetation of abandoned mine lands.

Part 1 of this paper reviews overall water-quality changes resulting from remining operations. Part 2 examines the impact of specific BMPs, individually or in combination with other BMPs (Hawkins et al., 2002.

A major goal of remining is that in the process of mining the remaining coal abandoned mine lands are reclaimed to present-day standards without the use of Federal Abandoned Mine Land (AML) funds or other public monies. Under the provisions of Pennsylvania's remining ("Subchapter F") regulations and the Rahall Amendment to the Federal Clean Water Act, the quality of preexisting discharges should be improved by remining operations. At a minimum, levels of pH, iron or manganese cannot be degraded from the pre-remining baseline condition. While this paper primarily discusses improvements in pollution load, remining sites that do not significantly change the water quality while achieving reclamation without the use of AML funds are also considered to have been successful.

Background
Pennsylvania's remining regulatory program requires the establishment of the baseline pollution load for any preexisting pollutional discharges that will be impacted by the remining operation (Pennsylvania Department of Environmental Protection, 1998). In most cases, this baseline consists of at least one year of monthly water-quality and flow data that are used to establish a statistical summary of the preexisting pollution load. Pollution load is the mass-loading rate of specific pollutants determined by multiplying concentration by the flow rate of the discharge as follows:

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$$\textit{Load}\ (\text{lbs/day}) = \textit{Conc.}\ (\text{mg/L}) \times \textit{Flow}\ (\text{gpm}) \times 0.01201 \quad (1)$$

$$\textit{Load}\ (\text{kg/day}) = \textit{Conc.}\ (\text{mg/L}) \times \textit{Flow}\ (\text{L/s}) \times 0.0864 \quad (2)$$

The baseline is summarized using the exploratory data analysis (EDA) techniques of John Tukey (Tukey, 1976; Smith, 1988; Pennsylvania Department of Environmental Resources et al., 1988). This summary is expressed by five key parameters — the range (extreme values), median, upper and lower quartiles, upper and lower 32^{nds} (approximate 95% tolerance values), and approximate 95% upper and lower confidence values around the median. This last pair of values represents the interval within which the true median value lies, with approximately 95% statistical certainty. EDA does not require normal distribution of baseline data, although it is common for pollution load data to be positively skewed and logarithmic transformation of the data may be employed to improve its statistical stability, i.e., narrow the confidence interval around the median.

Before Pennsylvania DEP issues a remining permit, the mine operator is required to determine the baseline pollution load from each individual preexisting discharge. Alternatively, where more than one discharge emanates from the same area, discharges may be physically or arithmetically combined into a single hydrologic unit, and the baseline calculated to reflect the aggregated pollution load from that hydrologic unit. On issuance of the remining permit, the operator is required to resume monthly flow and quality monitoring and calculate the pollution load from each discharge point or hydrologic unit. These data are submitted quarterly to the state regulatory authority, which conducts an annual review of the data to determine whether or not there has been any statistically significant degradation in water quality. A significant degradation triggers treatment of the discharge to baseline conditions. In addition, a review of the most recent 12 months of post-remining data is conducted at any time when the release of reclamation bonds is requested. Figure 1 illustrates how statistical summaries of the baseline and post- or during-mining data are used to determine if there has been a significant change in water quality. Any overlap between 95% confidence intervals indicates that an apparent change in median values is not significant at the 95% confidence level. If there is no overlap, then the change is considered to be statistically significant. For example, if the post-remining 95% confidence interval is below the baseline without any overlap, then the median pollution load is said to be significantly lower.

The principal objective in Pennsylvania's remining program is to achieve water-quality improvements through the implementation of BMPs in the remining operation. These BMPs include regrading, revegetation, daylighting of abandoned underground mines, special handling of acid-producing materials, alkaline addition, implementation of water handling systems, removal of coal refuse, biosolids addition, mining of highly alkaline strata, alkaline redistribution and incorporation of passive treatment into the mining plan. In addition to water-quality improvements, remining allows for the reclamation of abandoned mine lands to current standards at no cost to the public. Currently, the cost to reclaim all of Pennsylvania's abandoned mine land and to treat all abandoned mine drainage is estimated to be $15 billion. However, Pennsylvania receives only approximately $20 million per year in Federal abandoned-mine-land reclamation funds. The estimated average annual value of reclamation accomplished through remining is approximately $22 million (Pennsylvania Department of Environmental Protection, 1999, 2000), making remining a very significant contributor to the abandoned mine land reclamation effort.

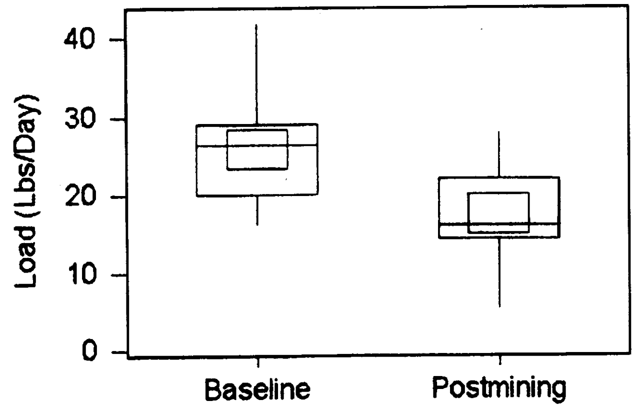

Figure 1 — Boxplot comparing postmining and baseline water quality. Outer rectangle defines upper and lower quartile values. Inner rectangle defines approximate 95% confidence interval around median. Horizontal line is observed median value and verticals show entire range in values. Overlap between confidence intervals indicates no statistically significant difference between medians. In this example, there is no overlap, and the postmining load is significantly less than the baseline load.

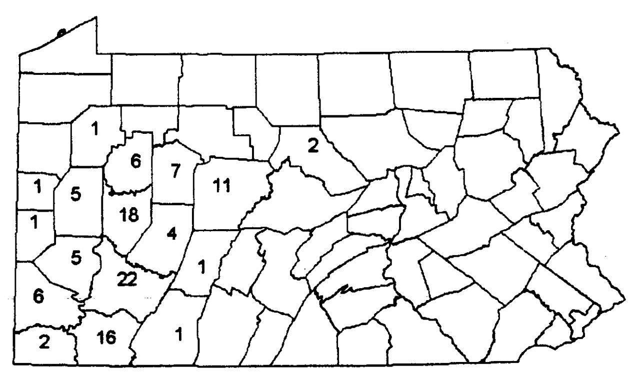

Figure 2 — Distribution of remining sites in the bituminous coal field of Pennsylvania that were examined for this study.

Study sites

The data used for this study were derived from mine sites located in the bituminous coal fields of Pennsylvania. Since 1984, PaDEP has issued over 300 remining permits with established baselines for preexisting discharges. At the time of this study (1999), mining and surface reclamation was completed on 112 of the more than 300 permits with 248 preexisting discharges. From that database, a data set of 110 reclaimed remining sites with 233 preexisting discharges was selected. Two remining sites were excluded from the study because of missing data. The distribution of these sites is shown in Fig. 2.

While this data set is the most extensive and comprehensive compilation of post-remining water quality available anywhere to date, the data do have some minor limitations and weaknesses:

Table 1 — Water-quality impacts of remining operations on preexisting AMD discharges in Pennsylvania.

Load		Number of discharges	Percent of discharges
Net acidity load	Eliminated	48	20.6
	Improved	61	26.2
	No change	122	52.4
	Degraded	2	0.9
	Total	233	
Iron load	Eliminated	51	24.5
	Improved	40	19.2
	No change	106	51.0
	Degraded	11	5.3
	Total	208	
Manganese load	Eliminated	35	21.6
	Improved	34	21.0
	No change	79	48.8
	Degraded	14	8.6
	Total	208	
Aluminum load	Eliminated	22	19.0
	Improved	24	20.7
	No change	66	56.9
	Degraded	4	0.3
	Total	116	
Sulfate load	Eliminated	41	18.4
	Improved	48	21.5
	No change	111	49.8
	Degraded	23	10.3
	Total	223	
Flow	Eliminated	40	17.6
	Improved	55	24.2
	No change	120	52.9
	Degraded	12	5.3
	Total	227	

- The data are exclusive to remining operations from the Pennsylvania bituminous coalfields. There may be some differences compared to other coalfields of the Appalachian Plateau, although coal-bearing strata throughout this region are geologically and hydrologically similar.
- There may be some bias introduced to the data set because only state-approved permits were included in the study. Permits that were deemed to be potentially detrimental to the environment were denied or amended with additional BMPs to preclude the possibility of further degradation.
- Recently reclaimed mines will likely not be completely representative of the final post-remining water quality and quantity, because the water table in the backfill generally takes 22 to 24 months to completely rebound (Helgeson and Razem, 1980; Hawkins, 1998) and some of the included sites have not been reclaimed that long. However, the majority of the mines included have been reclaimed for many years.

At the time of this study, only pollution loads and median flows were available. In some cases, baseline contaminant concentrations would be useful to determine which BMPs were most effective.

The data were not evaluated to determine if the pre- or post-remining sampling occurred during abnormal precipitation periods (i.e., extremely dry or wet conditions).

Data analysis methods

Post-remining data were compared to the pre-remining baseline to determine changes (increases and decreases) in pollution load for net acidity (total acidity less any alkalinity), iron, manganese, aluminum, sulfate and flow. For each discharge, the most recent 12 months of postmining pollution-load data were selected. Not all parameters were measured on all sites, depending on which parameters were of concern on that individual permit. Acidity, iron and manganese are regulated parameters. Aluminum, depending on the uses of the receiving stream, is frequently a regulated parameter; however, it is not statutorily mandated on the Federal level for remining. It was included in this analysis wherever data were available. Sulfate load and flow rate, although not regulated through effluent limitations, were also analyzed because they aid in performance evaluation and BMP efficacy determinations.

Post-remining data were collected for the same pre-remining discharges or hydrologic units and are representative of site conditions after the completion of reclamation. In cases where a discharge or discharges relocated following reclamation, the hydrologic unit approach was employed to identify discharges that were hydrologically related to the original preexisting discharge. Best management practices (BMPs) applied for each discharge were also identified, so that the effectiveness of specific pollution abatement methods could be evaluated separately.

The EDA analysis of pre- and postmining load, using a 95% confidence interval about the median, placed data into one of three categories: significantly improved, significantly degraded or the pollution load was unchanged. A fourth category, "eliminated," was added for discharges that were eliminated because of the remining operation.

If the upper limit of post-remining 95% confidence interval was below the lower limit of the pre-remining 95% confidence interval, then the pollution load was determined to be significantly decreased (see Fig. 1). Conversely, if the lower limit of the post-remining 95% confidence interval is above the upper limit of the pre-remining 95% confidence interval, then the median pollution load of that parameter was significantly increased. If the 95% confidence interval about the median for pre- and post-remining data overlaps, then the pollution load was determined to have no significant change due to remining. Lack of post-remining flow determined that the discharge was eliminated. Elimination of a discharge is defined as the discharge was physically eliminated or that with a 95% confidence the post-remining median was zero (US Environmental Protection Agency, 2001).

Effectiveness of remining

Table 1 is a summary of remining effectiveness for all 233 discharges from the 110 mines. On an overall basis, remining and the implementation of associated BMPs is shown to be highly successful in either reducing or eliminating pollution loads in nearly half of the preexisting discharges. Slightly more than half of the discharges exhibited no statistically significant difference in pollution load or flow because of remining. A much smaller fraction of discharges, less than 10% (except for sulfate), showed increased pollution loadings following remining. Flow was included in the data analysis, because it yields insight into whether changes in pollution

Table 2 — Baseline and post-remining pollution loads from preexisting AMD discharges in Pennsylvania.

Parameter	Number of mines	Number of discharges	Total baseline median load	Total post-mining median load	Total change in load	Percent change in median load	Percent change due to flow
Net acid load, lb/day	109	233	26,091	10,175	-15,916	-61.01	37.96
Iron load, lb/day	100	208	1,485	967	-518	-34.82	64.32
Manganese load, lb/day	75	162	246	216	31	-12.63	193.13
Aluminum load, lb/day	56	116	702	399	-303	-43.09	21.06
Sulfate load, lb/day	109	223	44,580	31,405	-13,175	-29.55	78.39
Flow, gpm	110	227	4,256	3,248	-1,008	-23.70	100.00

loading are caused by reduced discharge rates or actual changes in mine drainage chemistry.

More than 46% of discharges exhibited eliminated or reduced net acidity load. This is the greatest rate of improvement of all the parameters analyzed. The majority of discharges (52.4%) exhibited no significant changes due to remining. The failure rate (i.e., significantly degraded) was under 1%, the lowest of any parameter. The number of discharges exhibiting improvement for acid load compared to those showing degradation was over 50 fold. One reason for the high level of success in abating acid load may be due to the fact that the elimination of net acidity occurs in three ways – diminished flows, reducing the production of acidity and enhancing the production of alkalinity. Unlike other parameters that are unlikely to go to zero concentration, net acidity can be completely offset by the production of alkalinity.

Improvements in water quality, although still significant, are not quite as dramatic for metals — iron, manganese and aluminum. Pollution loads for iron, manganese and aluminum were significantly improved or eliminated at approximately 44%, 43% and 46%, respectively, of the discharges with preexisting load data. Approximately half exhibited no significant difference as a result of remining. The number of discharges that were significantly degraded was 5.3% for iron, 8.6% for manganese and 0.3% for aluminum. These figures appear to indicate a higher failure rate than actually exists in the field, because many of these discharges had very low baseline metals concentrations. It is not uncommon to have acidic discharges, with pre-remining metals concentrations of less than 1.0 mg/L. Although remining may have caused a statistically significant increase in loadings, the post-remining water quality nevertheless continues to meet Federal BAT effluent limits. This is born out by the low incidence of cases where a remining operator is deemed by PaDEP to have degraded a preexisting discharge and is required to treat or abate the discharge to pre-remining levels. Approximately 2% of preexisting discharges covered by remining permits in Pennsylvania have been identified as degraded below regulatory effluent limitations.

Except for sulfate loads, manganese exhibited the highest rate of discharges exhibiting significantly higher loads after remining and reclamation (8.6%), indicating that manganese is the pollutant least likely to show improvement through remining. Even so, the number of discharges that improved was more than 4.5 times the number that were degraded.

Sulfate load, while not considered in this context as a pollutant, was included in this study because it indicates geochemical changes within the backfill and at common concentrations it remains conservative (i.e., remains in solution). In the Appalachian Plateau, sulfate concentrations are directly related to pyrite oxidation and acid production. Sulfate loads had the highest percentage of discharges (10.3%) that were significantly degraded due to remining. Almost 40% of the discharges were significantly improved or eliminated by remining. Approximately half of the discharges (49.9%) showed no significant change. The number of discharges where the sulfate load was significantly lower was 3.8 times higher than the number that were made significantly worse.

Nearly, 53% of discharges showed no change in flow, while almost 42% exhibited a significant decrease in flow or were eliminated. Significant flow increases were recorded at 5.6% of the discharges. The number of discharges exhibiting significantly lower flow outnumbered those showing significantly higher flow by 7.4 to 1.

Aggregate changes in pollutant loadings. Table 2 shows the combined pollutant loading changes for all of the remining operations considered in this study. This table was calculated by adding the median loadings for each discharge under baseline and post-remining conditions. These summary numbers provide insights not readily evident through simply observing the number of discharges with significant changes in pollution loads.

Taken together, the combined impact of remining on the 110 study sites was to reduce acidity loadings by 61% or 7,219 kg/d (15,916 lbs/day). Over the course of a year, remining on these 110 sites has reduced the annual acid loading in Pennsylvania's bituminous coal region by more than 2.6 million kg (5.8 million lb) (US Environmental Protection Agency, 2001). Similarly, although not as dramatic, combined iron, manganese and aluminum loads are reduced by 235, 14 and 137 kg/d (518, 31 and 303 lbs/day), respectively. Again, manganese loads responded the least to remining, with the smallest overall percentage reduction. Combined sulfate load was reduced by over 5,900 kg/d (13,000 lbs/day) and the total median flow was reduced by more than 63 L/sec (1,000 gpm).

The role of hydrology in pollution loading reduction. A common assumption is that one of the chief mechanisms, if not the principal mechanism, that makes remining an effective tool in reducing pollution loads is that reclamation and revegetation of reclaimed mine sites reduces the availability of groundwater that would otherwise end up as acidic drainage. Data from this study was used to examine the role of flow reductions in effecting pollution load reductions and to determine the relative importance of flow versus changes in water chemistry. To do this, the median flow rate for each discharge was compared to the change in total pollution load to determine how much of the load reduction was due to a change in flow. The proportion of the loading reduction due to a change in flow was also calculated in aggregate for each parameter. This summary is also shown in Table 2.

For acidity, approximately 38% of the observed load reduction can be attributed to decreased flow. Therefore, the remaining 62% of the observed load reduction can be attributed to improvements in water quality, i.e., decreased acidity and increased alkalinity. For iron, 64% of the load reduction is attributed to flow changes. With aluminum, it is much lower at 21%, indicating that most of the improvement was caused by chemistry changes. This is probably due to aluminum being highly sensitive to pH changes. Manganese shows a very different result. Nearly 200% of the load reduction is attributed to changes in flow. This is interpreted to mean that post-remining concentrations of manganese actually increased; observed load reductions were entirely the result of flow changes. If concentration had remained constant, loadings would have decreased further. Sulfate load reductions were mostly (78%) the result of flow reductions. Remining does appear, however, to have had some effect in reducing pyrite oxidation.

Conclusions

In the bituminous coal fields of Pennsylvania, remining is a highly effective tool in reducing pollution loads from postmining acid mine drainage discharges left from abandoned mining operations. Nearly half of the preexisting discharges studied were significantly improved or eliminated through remining operations. Slightly more than half of the discharges exhibit no statistically significant changes in pollution loadings. A relatively small proportion of preexisting discharges, from less than 1% to 10%, depending on the parameter, had increased pollution loads following remining.

Taken together, remining on the 110 operations studied resulted in substantial pollution load reductions. Acid loadings were reduced by nearly 7,200 kg/d (16,000 lbs/day). A conservative estimate of the value of this load reduction is that it would cost approximately $3 million/year to treat this much acid load at a single treatment site. Of course, the cost to treat this much load at multiple sites would be substantially greater.

Pollution-load reductions resulted from a combination of both reduced flows and from improvements in water chemistry. The relative importance of flow reduction vs. changes in water chemistry varied by parameter. Aluminum load reduction was mostly due to chemistry change. Median manganese and sulfate load reductions were more impacted by reduced flows. Overall, it appears that both processes are roughly equal in their importance in effecting water-quality improvements.

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