ACID MINE DRAINAGE IN THE UNITED STATES

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INTRODUCTION

Any intensive use of the Earth's resources carries with it the potential for adverse environmental consequences. Mining is no exception. Almost 50 billion tons of old mining and mineral processing wastes lie scattered about the United States; over a billion tons more are generated each year. Environmental regulations now control mining and reclamation practices at most active operations, but past practices have left a legacy of sites contaminated by polluted mine water and subject to erosion by wind and rain.

In the United States, mining adversely affects over 19,300 km (12,000 miles) of rivers and streams and over 730 km^2 (180,000 acres) of lakes and reservoirs. At least a third of this contamination is due to acidic water generated by the exposure and weathering of pyrite (iron sulfide) (1).

Pyrite is a very common mineral, associated with most metal deposits and with many sedimentary rocks. It is formed in an anaerobic (very low oxygen) environment, and decomposes to iron and sulfuric acid upon prolonged exposure to the atmosphere. Because coal also forms in an anaerobic environment, coal and the rock strata surrounding many coal beds often contain high concentrations of pyrite. In fact, pyrite content is the most important parameter that distinguishes "high sulfur" from "low sulfur" coal. In the eastern United States, acid mine drainage (AMD) is primarily associated with the mining of coal; in the western United States, it is principally a result of mining metallic ores. The same two source types are responsible for most AMD problems in the various mining regions of the world, subject to local rainfall and depth of mining, both of which influence whether or not surface drainage occurs at all.

The effect of AMD on streams and waterways can be very dramatic. In the worst cases, virtually all aquatic life disappears, river bottoms become coated with a layer of what looks like rust particles, and the pH plummets. By way of comparison, acid rain has a titratable acidity of 10-15 mg/L (a measurement that reflects the amount of alkaline material [$CaCO_3$] required to neutralize it). AMD is typically 20-300 times more acidic. As a result, acid rain is principally a problem where the rocks and soil contain very little alkalinity. AMD, though much more localized in its influence, is more concentrated, and in sufficient volume, can overwhelm the normal buffering capacity of almost any stream.

However, there is some good news. In the last 20 years, the adverse impact of AMD in the U.S. appears to have decreased by about one-third (Fig. 1) (1,2). This comparison is vulnerable to differences in the intensity of sampling and the criteria the various states have used to classify a stream as degraded, but the general trend is certainly valid. Most of this improvement is due to chemical neutralization before the mine water is discharged, now required at all mines that are now, or have ever been, active since passage of various Federal laws during the 1970's. The cost of this chemical treatment, nationwide, is estimated by the author to exceed one million dollars a day. In addition, a voluminous iron-rich sludge is generated; at most sites, this represents a disposal problem (3).

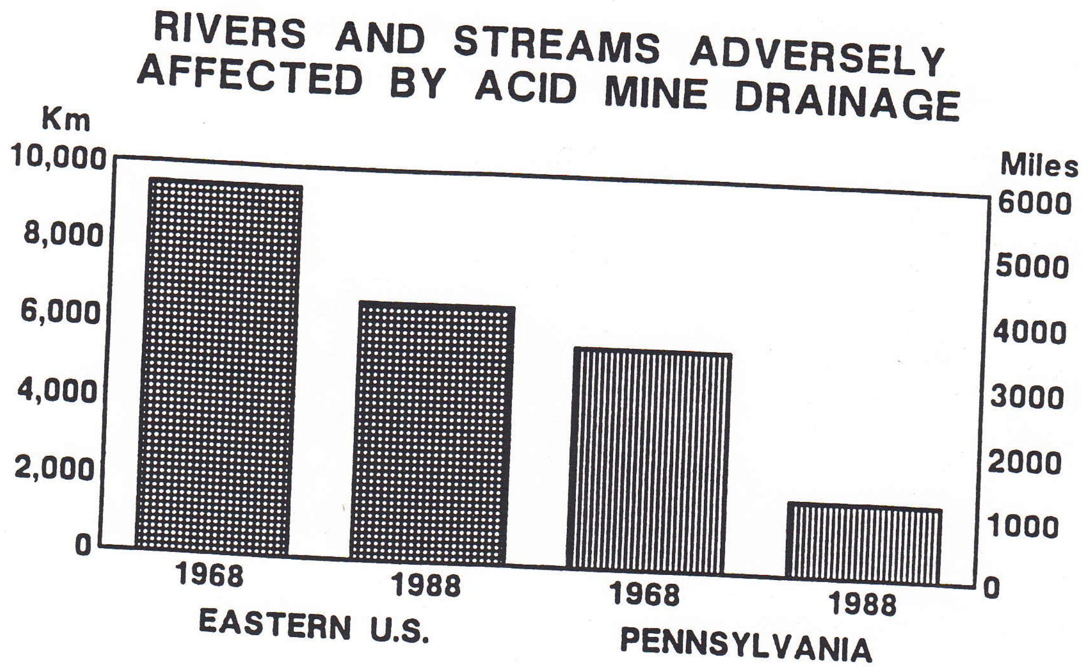

FIGURE 1

Other factors that have contributed to improved stream water quality are reclamation of abandoned mines, natural amelioration (such as where exposed pyrite is limited and has already oxidized) and a dedicated research effort targeted at the AMD problem. The AMD that continues to degrade stream quality is almost exclusively associated with mines closed and abandoned before the current regulations went into effect. Reclamation is being conducted using revenue collected from active coal mining operations, which are taxed at 15 or 35 cents a ton (underground and surface mines, respectively). In addition, new approaches have been, and continue to be, developed to solve the AMD problem. In the rest of this paper, case studies will be used to document the improvement that has occurred in AMD-contaminated watersheds, and then new technology that has been developed to combat the AMD problem will be discussed.

WATER QUALITY IN MINED WATERSHEDS

As a result of approximately 200 years of coal mining, the state of Pennsylvania has a severe AMD problem. Twenty years ago, more than half of the

U.S. streams degraded by acidic coal mine drainage were in Pennsylvania. About two-thirds of these watersheds are no longer seriously affected by AMD (Fig. 1). For example, in western Pennsylvania, water samples collected at the junction of the Monongahela and the Youghiogheny Rivers indicate that in 1934, the Youghiogheny River had an acidity of 80 mg/L (as $CaCO_3$). By 1960, the acidity had decreased to about 18 mg/L in the Youghiogheny River, apparently due to the construction of reservoirs (4). A recently-completed analysis of water quality records for the Youghiogheny River indicates that acidity has continued to decrease, averaging 12.2 from 1965 to 1967, 9.0 from 1976 to 1977, 6.5 from 1978 to 1984 and 1.8 from 1985 to 1987. Most of this subsequent improvement is probably due to enactment and enforcement of effluent limits for the area's active mines.

As an example of water quality improvement unrelated to chemical treatment, one can look at the water quality in eastern Pennsylvania, where the mining of anthracite coal was once a thriving industry. These old mines were abandoned and allowed to flood over 25 years ago. To protect surface structures, near-surface drainage tunnels, known as outfalls, were constructed to limit the recovery of the water table. The Askam, Buttonwood and South Wilkes-Barre outfalls now drain a mine pool estimated to contain 6×10^7 m^3 (1.6×10^{10} gal) of mine water. The three outfalls together discharge about 2 m^3/s (32,000 gal/min) of untreated acidic water into the Susquehanna River (5). The inundation of the mine workings curtailed pyrite oxidation by limiting atmospheric contact. Though acidic water already formed must be flushed out, very little new AMD is forming. As a result of inundation, acidity at the outfalls decreased 74 pct and sulfate concentrations decreased 49 pct during the period 1968 to 1979. (The decrease in sulfate indicates that the improvement is not simply caused by neutralization). The pH observed ranged from 3.3 to 5.6 in 1968; by 1979, this had improved to 5.8 to 6.2. Sampling of water in the flooded mine workings by the Bureau of Mines indicated that the water quality at the outfalls should continue to improve, for 93 pct of the mine shaft water samples collected were alkaline, with pH's as high as 7.8 (5).

A third Pennsylvania example documents the effect of reclamation and natural amelioration. The Turtle Creek Watershed encompasses 381 km^2 (147 square miles). Underground mining was active in the area from 1854 to the 1930's. There was also some surface mining in the 1940's, and one small surface mine continued to operate until fairly recently. Water quality in the Turtle Creek watershed was severely impacted by AMD; despite its name, 26 km (16 miles) of stream water was essentially barren until the early 1970's. Estimates on what would be required to control AMD and restore a fluvial ecosystem in the watershed exceeded 11 million dollars. Though Federal and State money (funded through a tax on coal produced and publicly-issued bonds, respectively) are available for reclamation of abandoned mines, the lack of life-threatening conditions and the relatively small size of the impacted area weighed against such an expenditure. In fact, actual expenditures used to control AMD in the watershed probably did not exceed one million dollars; these funds were used to seal some mine openings that were allowing uncontaminated mine water to enter the old mine workings and become polluted. Nonetheless, water quality began to improve during the 1970's and early 1980's, to the point that fish and turtles can now once again live there. Most of this improvement can probably be attributed to natural causes, as the most readily oxidized pyrite was gradually consumed.

NEW AMD CONTROL TECHNOLOGY

The effect of AMD on stream water quality, though only two-thirds of what it was approximately a decade ago, continues to be a major problem for the U.S. It is now principally associated with old abandoned mines; if these sources are to be controlled, it will be at public expense. In adition, the long-term liability of water treatment has become a significant expense factor that affects commodity prices and operable reserves. Nevertheless, research developments provide some basis for optimism.

Passive Treatment of AMD

One such development is the discovery that wetlands can be established in acidic mine water, and that these wetlands actually help to purify the water. As a result, during the past few years, over 400 small wetlands have been constructed on mined lands for the primary purpose of water treatment. In general, they consist of a series of shallow ponds planted with cattails (*Typha*) (Figure 2). Most of these biological treatment systems have been constructed by active mining operations to reduce their water treatment costs; in general, the wetlands have paid for their construction costs in less than a year. In addition, an increasing number are being constructed by state agencies at abandoned mine sites, where improvements in effluent water quality can directly affect the quality of receiving streams.

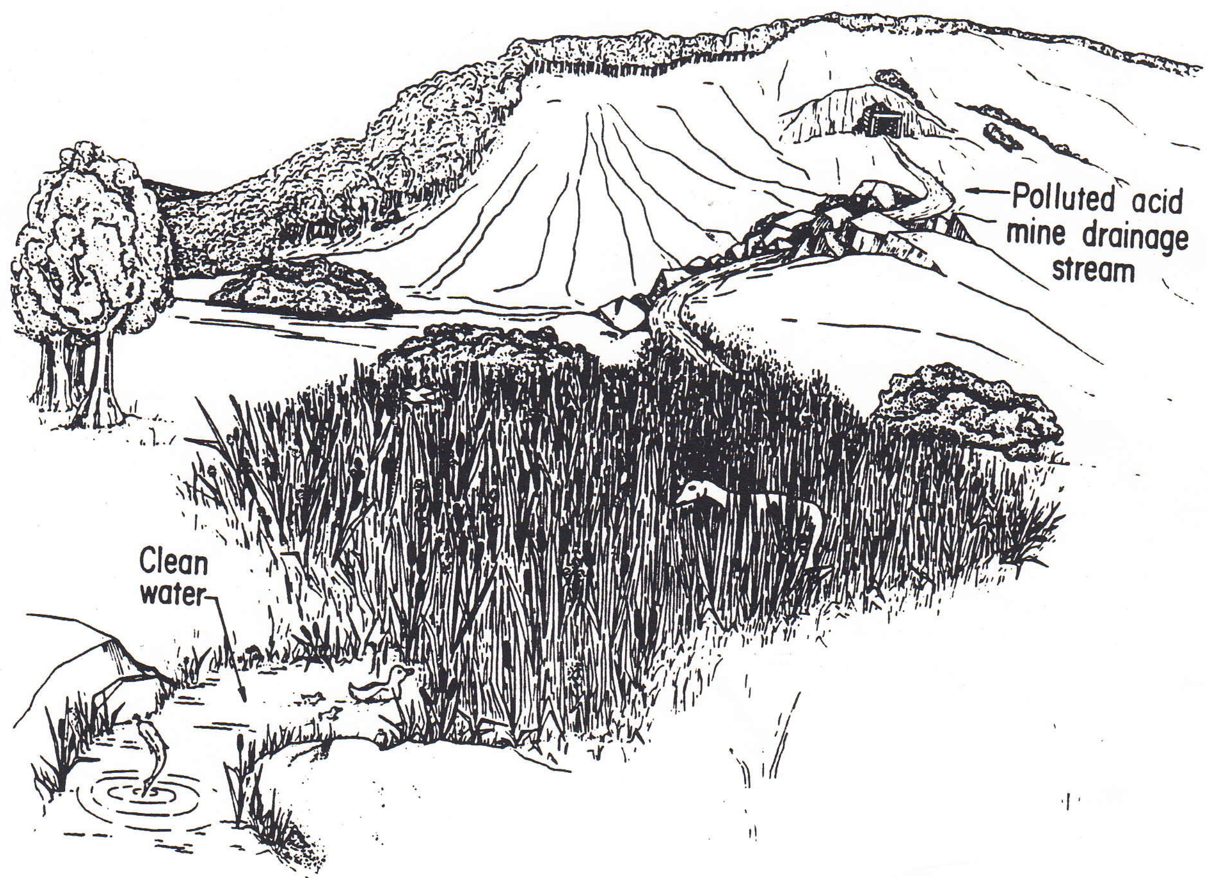

FIGURE 2

The principle treatment process in most of the wetland systems is bacterial oxidation of iron, and to a lesser extent, manganese. For this reason, most wetlands have been constructed at coal mines rather than metal mines. Metal uptake by plants, algae and even the substrate contributes somewhat, but is limited by the amount of biomass. Some neutralization also occurs, due to sulfate reduction and dissolution of limestone in the anaerobic zone.

The Bureau of Mines is developing empirical sizing criteria, based on iron removal, that takes into account water chemistry as well as flow rates. If the influent water has a pH above 6, it appears that 250 ft^2 will remove a pound of iron a day. If the influent pH is 4-5, twice as much space is required. At a pH of 3.0-3.5, at least 12,000 ft^2 is required to remove the same iron load. Finally, if the wetland is also expected to improve pH and/or lower manganese concentrations, even more space is required.

Another passive technique to treat acid mine drainage, anoxic alkaline drains, has recently been developed. Water that is low in oxygen, with iron in the ferrous (Fe^{2+}) rather than the ferric (Fe^{3+}) form, is intercepted by a limestone-filled trench. The limestone is isolated from the atmosphere by plastic sheeting and a clay cap to prevent iron oxidation and armoring of the limestone by ferric hydroxide. Dissolution of the limestone has raised the pH from less than 4 to over 6 at several field sites (6). Longevity of treatment is an obvious concern; to date, the oldest test system has been functioning for 20 months. This is, however, already three times as long as previous similar systems that did not contain the plastic sheeting, giving some reason for optimism. As already noted, the efficiency of constructed wetlands is directly affected by influent pH. Anoxic alkaline drains would therefore appear to be a useful initial step for a biological treatment system; Tennessee Valley Authority (TVA) has already begun to combine the two systems in that manner (7).

Currently, Bureau of Mines scientists are focusing on optimizing the activity of sulfate reducing bacteria that thrive in the wetlands' anaerobic zone. Not only does the activity of these bacteria consume acidity, the hydrogen sulfide they produce reacts with most heavy metals to produce virtually insoluble precipitates. This would greatly increase water treatment efficiency, avoid the problem of sludge accumulation associated with the oxidation and hydrolysis reactions and extend the applicability of biological treatment to metal mines (8,9). It should also be noted that sulfate reduction systems, once perfected, may not require a wetlands system. Within a few years, we hope to have developed septic systems that will function in abandoned pits or even perhaps abandoned underground entries, requiring only periodic addition of organic materials to fuel the sulfate-reducing reactions (10).

At-source Control Technology

An alternative to treating the acidic water is to abate the acid generation at its source. The generally accepted method of curtailing AMD generation is to inundate the pyritic material, thereby virtually eliminating pyrite oxidation. This has proven to be successful if inundation is complete, such as in the anthracite example cited earlier. Incomplete inundation, usually caused by the dip of the mined seam or vein, or water table fluctuations, simply moves the active oxidation zone to a higher elevation in the mine or spoil without reducing acid formation.

An alternative approach, developed by Bureau researchers several years ago, involves the inhibition of the iron-oxidizing bacteria responsible for the rapidity of pyrite oxidation. Anionic surfactants (common cleansing detergents) can be used to decrease the activity of these bacteria and thereby retard pyrite oxidation. This approach is most applicable to coal refuse piles, where acid production has been reduced 60-95 pct (8). Laboratory tests with metal mine waste indicate great variability in the significance of the iron-oxidizing bacteria in acid generation; small-scale tests should therefore be conducted before field trials at metal mine sites are considered (9).

The surfactant can be sprayed on (3 times a year) or applied in controlled-release formulations that inhibit pyrite oxidation for 5 to 10 years. Both approaches are now commercially available. Research is planned on possible ways to extend this technology for use underground.

Other approaches to at-source control utilize chemical additions to provide neutralization in place and to retard pyrite oxidation by armoring or precipitating reactants. Typically, an alkaline compound is used; one problem is that the volume of acidic water represents a large acid load that must all be neutralized. Alkaline injection has generally proven inapplicable for surface mines, due to the relatively short-lived residence time and heterogeneous flow, but Bureau researchers are now considering its applicability for underground mines, where large pools of acid water could be periodically neutralized. Alternatively, at surface mines, surface application of alkalinity can be effective at sites where acid formation rates are modest. Also, university researchers at West Virginia and Montana State are evaluating the economics of using phosphate rock to form iron phosphates, thereby curtailing pyrite oxidation.

Reducing pyrite-water contact can also reduce the volume of AMD that forms. One recent development reduces the volume of water that leaks into underground mines from streams by 90 pct or more. Leaking zones are pinpointed using terrain conductivity (a simple and rapid geophysical technique) and verified by conventional gaging methods. The fractured streambed is then mended using a polyurethane grout injected beneath the sediment-water interface. The cost per linear foot is as low as half that of conventional stream repair, in addition to the savings realized by specifically targeting the water loss zones. Long-term prospects are also superior, since the grout-sealed streambed is not subject to damage by storm events or tree growth. Tests in streams above active longwall operations and an old, abandoned room-and-pillar mine have been extremely successful (10).

CONCLUSION

Acid mine drainage is an extremely persistent form of water pollution, and causes significant degradation of water quality in mining regions around the world. The United States has addressed this problem by strictly regulating the effluent waters from mining operations, by reclaiming abandoned mines and by developing new techniques to improve the quality of mine water at active and abandoned mining operations. Active mining operations contribute to the cost of reclaiming abandoned mines through a special tax on each ton of coal mined, and in addition spend over one million dollars a day to treat contaminated mine water from operations that are, or have been recently, active.

As a result, the adverse effects of acidic mine water on the streams and rivers of the United States has been substantially reduced. The AMD that remains originates at long-abandoned mine sites. Recent research developments should help to further reduce the impact that this AMD has on the waterways of the United States.

REFERENCES

1. Compiled by the author from 305-B reports from mining-affected states, supplemented by personal communications with the following state agencies: Alabama Dept. of Environmental Management, Arkansas Dept. of Pollution Control and Ecology, Kansas Dept. of Health and Environment, Kentucky Dept. for Environmental Protection, Illinois Environmental Management, Maryland Dept. of Environment, Missouri Dept. of Natural Resources, Ohio Environmental Protection Agency, Oklahoma Dept. of Pollution Control, Pennsylvania Dept. of Environmental Resources, Tennessee Dept. of Health and Environment, Virginia Water Control Board, and West Virginia Dept. of Natural Resources.

2. Appalachian Regional Commission. Acid Mine Drainage in Appalachia, 1969, 126 p.

3. Ackman, T. E. Sludge Disposal From Acid Mine Drainage Treatment. BuMines RI 8672, 1982, 25 p.

4. Clark, C. S. Some Factors Involved in the Oxidation of Coal Mine Pyrite and Water Quality Trends in the Monongahela River Basin. In: Proceedings of the Symposium on Acid Mine Drainage Research, Mellon Institute, Pittsburgh, PA, 1965, pp. 35-56.

5. Ladwig, K. J., P. M. Erickson, R. L. P. Kleinmann, and E. T. Posluszny. Stratification in Water Quality in Inundated Anthracite Mines, Eastern Pennsylvania. BuMines RI 8837, 1984, 35 pp.

6. Turner, D. and D. McCoy. Anoxic Alkaline Drain Treatment System, a Low Cost Acid Mine Drainage Treatment Alternative. In: Proceedings, 1990 National Symposium on Mining, D. H. Graves (ed.), Univ. of KY, 1990, pp. 73-75.

7. Brodie, G. A. Treatment of Acid Mine Drainage Using Constructed Wetlands, Experiences of the Tennessee Valley Authority. In: Proceedings, 1990 National Symposium on Mining, D. H. Graves (ed.), Univ. of KY, 1990, pp. 77-83.