Long-Term Performance of Passive Acid Mine Drainage Treatment Systems

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ABSTRACT

Passive acid mine drainage (AMD) treatment systems were developed over the past 20 years to provide reliable, low cost, low maintenance treatment of mine drainage in remote locations. Passive treatment methods can be grouped into about nine categories, including aerobic and anaerobic wetlands, ponds, anoxic limestone drains (ALD), ALD-wetland systems, open limestone channels (OLC), vertical flow wetlands (VFW), and limestone and slag leach beds (LSB and SLB). We evaluated the performance of these methods by studying 137 treatment units in the midwest and eastern U.S. We collected initial design and cost information, sampled the water quality and quantity in and out of the systems, and determined the individual treatment effectiveness of each unit. Performance was normalized according to construction cost, projected service life and tons of acid load treated and dimensioned as $/tons of acid load treated/year. These costs were then compared to those of chemical treatment. Sites that achieved acid load reductions at costs below those of chemical treatment were considered successful. The results indicated a high success rate for several passive treatment methods (SLB, LSB, ALD, and OLC), while others were not so successful. While it appears that passive systems are effective for AMD treatment, improved reliability and efficiency are needed. This report is an initial step toward measuring passive treatment system performance among various categories of treatment types. Additional work is needed to document specific causes of success and failure.

INTRODUCTION

Acid mine drainage (AMD) forms when sulfide minerals are exposed to oxidizing conditions by mining, highway construction, and other large-scale excavation. There are many types of sulfide minerals throughout the world in different mining districts. This paper focuses on AMD treatment in coal mining settings of the eastern U.S.

Upon exposure to water and oxygen, iron sulfides oxidize to form acidic, sulfate-rich drainage. Metal ion concentrations in AMD depend on the type and quantity of sulfide minerals present as well as host rock composition. Acidity in AMD is comprised of mineral acidity (cations of Fe, Al, Mn,) and hydrogen ion acidity (measured as pH units). AMD chemistry is a function of site hydrology and its supply of acid-producing (sulfide) and alkaline (carbonate) minerals. In general, sulfide-rich and carbonate-poor materials produce acidic drainage. In contrast, alkaline-rich materials, even with significant sulfide concentrations, often produce alkaline water.

Approximately 20,000 km of streams and rivers in the eastern U.S. are degraded by AMD. About 90% originates in abandoned surface and deep coal mines. Since no company or individual claims responsibility for reclaiming abandoned mine lands (AML), any treatment action becomes a public responsibility.

When AMD is neutralized, its dissolved metals precipitate as low density flocculates (sludge). Therefore, most AMD treatment systems involve two steps: alkalinity addition (acid neutralization) and metal precipitation. Treatment systems fall into two categories: active and passive. Active or chemical treatment systems involve continuous dosing of the AMD stream with a base such as lime, caustic soda, soda ash briquettes, or ammonia, and several reports are available that consider the site requirements,

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types of water, and costs for treating AMD with these chemicals (Skousen and Ziemkiewicz, 1996). Such systems require regular access and maintenance to maintain chemical supplies, power, pumps and the sludge handling system. Such systems are reliable and effective but their cost, power and maintenance requirements make them impractical for most remote abandoned mine locations.

Over the past 20 years, a variety of passive treatment systems have been developed that do not require continuous chemical inputs while taking advantage of naturally occurring chemical and biological processes to improve contaminated waters. The primary passive technologies include: constructed wetlands, ponds, anoxic limestone drains (ALD), vertical flow wetlands (VFW), open limestone channels (OLC), limestone leach beds (LSB), and slag leach beds (SLB).

MATERIALS AND METHODS

Forty-nine sites with 137 separate treatment units were chosen throughout the eastern U.S. (Alabama, Indiana, Kentucky, Maryland, Ohio, Tennessee and West Virginia) as part of an ongoing passive treatment evaluation conducted in support of the Acid Drainage Technology Initiative. Information on the design, construction, and cost of each system was gathered and water quality data for each site was collected. Flows were measured by a bucket and stopwatch, by flow meters, or in a few cases by estimation at the inflow and outflow of each treatment unit. Acidity and alkalinity were measured by certified laboratories in the respective states. In this way, the amount of acid removed by each component of the system could be estimated.

For many sites, however, the data did not permit comparisons of incoming and outgoing water from a given treatment unit. For example, ALDs generally did not afford measurement of influent flow and acid concentration, so we only could use water quality and quantity information gathered before the system was installed. Between one and five data points were used for each treatment unit and these data points were averaged. This did not permit analysis of performance trends over time. Some sites had only one type of passive system installed on the site, while most of the sites had a combination of types. Analysis of the data depended on estimating four key parameters: acid load treated, passive treatment unit costs, active treatment costs and service life.

Acid Load: In some cases, it was possible to obtain water samples upstream and downstream of the treatment unit. These data were always used. On other sites, either because of construction methods or sampling strategies, upstream water quality could not be determined when the downstream samples were taken as noted earlier. In these cases, we used pre-construction water quality, which data is clearly of lower reliability. In other cases, we sometimes had ten downstream samples, but only one upstream sample. In these cases we would only use those data collected on the same date.

Passive Treatment Unit Costs: Personnel from various state abandoned mine land programs, federal Office of Surface Mining offices, and universities determined the total project cost for each site based on the contractor's costs. These costs usually included the total cost for the site: access, regrading, seeding, fertilization and water management. Items such as access/road construction and transportation are specific to the particular site. Rarely was it possible to isolate costs for individual treatment units within a site by using these figures. Therefore, we estimated the cost of building the individual treatment units by using a set of standard rates for building passive systems. These rates were \$3 per cubic yard for excavation, \$25 per ton of limestone, \$25 per ton of slag, \$70 per ton of calcium hydroxide, and \$25 per cubic yard of organic matter. Treatment unit dimensions were generally available, so we were able to calculate these costs and we relied on estimated costs for the cost efficiency evaluations. This provided a constant basis for comparing the cost per metric ton of acid removed for each treatment unit.

Active Treatment Costs: In order to compare the costs of passive treatment to conventional chemical treatment, we estimated the annual cost of treating a metric ton of acid load with caustic soda (NaOH). This proved to be \$500/ton/year. This includes only the delivered chemical cost of caustic soda. It does not include equipment, labor, sludge pond construction, cleaning, piping etc. Inclusion of these factors would normally double or triple the cost.

Service Life: Service life is the expected period of performance for a given treatment unit. It was estimated on the basis of the limestone consumption rate. Service life (years) was estimated by dividing the limestone mass by annual acid load treated by 80% (average neutralization potential of limestone). By this process, some units had an estimated service life of only two years, while a number of treatment units were removing acid load so slowly that the limestone supply would last for several hundred years. In fact, it is expected that these units will fail by some other means long before they exhaust the limestone. Therefore, we assigned a maximum service of 20 years to all treatment units. Where available, actual service life data supplied by local personnel were used on those sites where unit failure had been determined.

Positive treatment for each system was defined as less acid load coming out of the system than going in. We used this as a gauge to evaluate treatment effectiveness. Successful treatment was based on costs to treat the water. The annual cost of acid load removal ($/metric ton/year) was estimated for each treatment unit. For those units that gained acid load, this parameter could not be determined since limestone consumption would be zero and service life would be determined as infinite. Controlling service life at 20 years would not solve the problem since metric tons of acid load treated would also be zero, thus dividing cost by zero. Such estimates would be useless, so sites which gained acid load were classified as failures and excluded from further cost effectiveness analysis.

Treatment success versus failure of an individual treatment unit was based on the cost to install the system and the amount of acid the system treated compared to the cost of treating the same amount of acid with a chemical system (caustic soda at a cost of $500/ton/year). If the cost of water treatment for the passive system was <$500/ton/yr, then the passive system was considered successful. Since the performance of passive treatment systems often declines rapidly after the first 6 to 12 months, only the most recent 2 to 3 years of performance monitoring data were used in this study.

A total of 137 passive treatment systems on 49 remediation sites were evaluated. While the long-term performance trends and actual service lives of passive treatment systems are yet to be determined, this study assumed that the performance over the past several years would persist until the limestone was exhausted or to a maximum of 20 years. The point of limestone exhaustion or service life was estimated by the following formula:

$$\text{Service life (years)} = \frac{\text{Mass of Limestone (tons) x Limestone purity (\%NP)}}{\text{Acid removal rate (tons/year)}}$$

Performance data were confounded to various degrees by several factors. First, there may have been a poor fit of system to site: trying to treat a high Al water with an ALD, installing an OLC on a flat channel, inadequate flushing of a VFW, or simply making poor hydraulic connections between incoming water and the treatment system. Any of these factors would result in a lower performance rating for the method. Our analysis did not account for such factors. Second, there may be uncontrolled and undocumented inflow of acid or alkaline water to the system. Third, pre-construction estimates of incoming quantity and quality may not reflect current inflows. While we made every attempt to control the latter two factors in the data analysis, it was not always possible given the sampling scheme. On the other hand, application of a method to the wrong site or inadequate maintenance is simply recorded, perhaps unfairly, as a failure of that method.

RESULTS AND DISCUSSION

Aerobic Wetlands: Performance of the aerobic wetlands was highly variable. They removed between -3.6 and 14.3 tons of acid per year at costs ranging from $23 to $1,512/ton/year over the expected 20-year lifetime (Table 2). These wetlands often received pre-treated water that had passed through an ALD or VFW. Seventy eight percent of the aerobic wetlands achieved either acid reduction or net alkalinity generation. However, the costs were often high. As a result, only 44% of the aerobic wetlands were efficient enough to be considered successful. Optimal aerobic wetland performance is expected when the pH is about

6.0 or above. All of the successful aerobic wetlands fell within this pH influent range, although two receiving water above pH 6.0 were too expensive to be considered successful. The least efficient aerobic wetland was found at WV-10a, where the incoming water had a pH of 2.5.

AMD Treatment Ponds: The AMD treatment ponds (Table 3) were generally designed to capture and retain water to allow for metal hydroxide oxidation and precipitation. Since metal ion oxidation generates acidity, it was expected that the ponds would be net acid producers. Nonetheless, they were analyzed independently to isolate their treatment effects and costs. Of the 18 ponds, seven gave positive treatment, but only four did so efficiently. The acid treatment costs for these systems were between $58 and $3,000/ton/year. Eleven ponds yielded negative treatment, meaning more acid exited than entered. In addition to oxidation effects, acid production could result from undocumented inflow of acidity or release of acid from pyritic sediments.

Anaerobic Wetlands: The 10 anaerobic wetlands with positive treatment showed wide variation in treatment costs from $138/ton/year at WV-4b to $3,912 at WV-1h (Table 4). Five of the 18 sites provided efficient treatment (cost of <$500/ton/year), while eight anaerobic wetland sites gave negative treatment and failed according to our criteria.

Anoxic Limestone Drains: There were 38 ALDs evaluated in our study and 33 gave positive treatment (Table 5). Of these, 29 were successful, showing costs <$500/ton/year. In fact, almost half of the ALDs were <$100/ton/year, and nine units were <$70 per ton. There was no apparent relationship between the pH of incoming water and the ALD's effectiveness. Assuming that the ALDs would perform over the expected lifetime, these were the most consistently efficient passive treatment systems in terms of the cost per ton of acid removed.

ALD/Wetlands: Four ALD/Wetland combinations (Table 6) were installed at three West Virginia sites. The acid treatment cost varied between $122 to $9,493/ton/year. Three of the four provided successful treatment.

Vertical Flow Wetlands: The 16 VFWs with positive treatment showed wide variation in treatment cost from $39 at a Maryland site to $2,023/ton/year at a West Virginia site (Table 7). Three VFWs had negative treatment, and these sites either discharged much greater than the design flows or discharged lower quality water than at the inflow.

Open Limestone Channels: Eleven OLCs were evaluated in this study, and 10 of 11showed positive treatment and 8 of 11 gave successful treatment (Table 8). One OLC at WV-12a showed negative treatment.

Limestone Leach Beds: Limestone beds have been extensively installed in Alabama and Tennessee. All 18 systems gave positive treatment, and 14 treated acid at <$500/ton/year (Table 9). These, along with ALDs, were among the most efficient systems in this study. These systems removed between 0.4 to 59 metric tons of acid load per year.

Slag Leach Beds: Two steel slag leach bed systems were installed in Ohio and West Virginia. Both systems showed positive acid treatment at very low treatment costs (Table 10). The Ohio system treated the most acid, 313.6 ton/year, and was the most cost efficient, $12/ton/year, of all the systems in the study.

CONCLUSIONS

This study evaluated the performance of 137 passive systems. They included aerobic and anaerobic wetlands, sedimentation ponds, anoxic limestone drains (ALD), ALD-wetland combination systems, limestone and slag leach beds (LSB and SLB), open limestone channels (OLC), and vertical flow wetlands (VFW). While performance has been reported for individual systems, there has not been a comprehensive evaluation of the performance of each treatment method over a wide variety of conditions. Most of eastern and midwestern U.S. coal states have constructed passive AMD treatment systems. In addition, citizen-based watershed organizations have constructed systems with assistance from federal and state programs. We collected initial design and cost information, sampled the water quality and quantity in and out of the systems, and determined the individual treatment effectiveness of each unit.

Positive treatment was defined as a reduction in acid load. Treatment success or failure was based on the cost to install the system and the amount of acid the system treated compared to the cost of treating the same amount of acid with a chemical system (caustic soda). The sites ranged in age from 1 to 12 years since construction.

Of the 137 systems, 107 showed positive treatment. Seven of the nine aerobic wetlands in the study removed some acid from the incoming acidic water, but only four (44%) removed acid at a cost below that estimated for chemical treatment. Ten of 18 anaerobic wetlands showed positive treatment, and only five of the 18 showed treatment costs lower than chemical treatment (28%). Seven of 18 ponds showed positive treatment, and four of 18 ponds (22%) provided treatment cheaper than caustic. Thirty-three of 38 ALDs removed acid and 29 of 38 (76%) were successful. There were four ALD-wetland combination systems with all showing positive treatment and three systems showing treatment success (75%). All 18 limestone beds evaluated in this study showed positive treatment and 14 were successful (78%). Eleven OLCs were studied and 10 gave positive treatment and eight were successful (73%). Sixteen of the 19 VFW in this study gave positive treatment, and nine were successful (47%). Both of the SLBs gave positive and successful treatment.

In most cases of negative treatment, the systems apparently gained water downstream of the inflow measurement point since flows, rather than acidity concentrations, generally increased. Many systems treated water effectively but at excessive cost, most often a result of over sizing. Other systems treated water efficiently but were under-sized resulting in discharge of poor water. In some cases, the passive treatment method was applied to a setting for which it was not suited.

Treatment unit performance (efficiency) was ranked according to $ per ton of acid load treated per year of service life. The values ranged from $12 to $9,493 per ton. Out of 107 treatment units, 35 recorded cost efficiencies of <$100/ton/year. In addition, 77 of the 107 sites treated the water for <$500 per ton, a lower cost than by using caustic soda. Again, only chemical caustic costs were used in these comparisons. This value excluded additional treatment costs such as capital cost, resupply, adjustment of treatment rate, manpower, and sludge collection and handling.

The maximum amount of treatment was 313.6 tons per year and the lowest was 0.02 tons per year. High levels of treatment generally correlated with high treatment efficiencies (low cost/ton/year). Total unit cost tended to be weakly correlated with total tons treated, but not with efficiency.

The 107 positive treatment systems treated 1767 tons of acid per year. The 107 positive treatment systems had a cumulative cost of $5,177,455 and the 30 negative treatment units had a cumulative cost of $560,455. Therefore, of the total $5,737,910 spent on passive treatment systems, 90% of the money was spent on successful systems. Treating the same amount of acid load with caustic would have cost about $883,500 per year. At this chemical treatment rate, the passive treatment systems would break even with caustic treatment costs within 6 years.

Table 11 summarizes the performance of the various treatment types. Steel slag leach beds and limestone beds had the highest success ratio (100% and 78%, respectively), and a high average acid treatment of 166.3 and 17.3 tons/year at an average cost of $48 and $664 per ton/year of acid. Anoxic limestone drains (ALD) were 76% successful, treating 16.8 tons/year of acid at an average cost of $214 per ton/year. The ALD/Wetland systems had a high success rate of 75%, and treated an average of 8.3 tons of acid/year at a cost of $2,557/ton/year. The OLCs were 73% successful and had a high average acid treatment of 8.7 tons/year. Vertical flow wetlands were 47% successful, with an average cost of $588/ton/year, while aerobic wetlands were 44% successful and treated 3.6 tons/year of acid at a cost of $479/ton/year. Anaerobic wetlands were 28% successful, while Ponds were around 22% successful. Interpretation of the results should recognize the disparity in the number of units per treatment type. There were only 2 SLBs and 38 ALDs. Some of the most expensive methods had the lowest success ratios.

Passive system designers and reclamation planners will want to know which techniques provide the greatest return per dollar. The results of this analysis indicate that three methods provide a high level of reliability (success vs failure), high acid load removals, and low treatment cost. These three are limestone beds, ALDs, and OLCs. Future monitoring will improve the database and improve the reliability of these conclusions.

REFERENCES

Eger, P. 1994. Wetland treatment for trace metal removal from mine drainage: The importance of aerobic and anaerobic processes. Water Sci. Technol. 29:249-256.

Hedin, R.S., R.W. Nairn, and R.L.P. Kleinmann. 1994. Passive treatment of coal mine drainage. USDI, Bureau of Mines Information Circular IC 9389. Pittsburgh, PA.

Hyman, D.M., and G.R. Watzlaf. 1995. Mine drainage characterization for the successful design and evaluation of passive treatment systems. In: Proceedings, Seventeenth Annual Conference of the National Association of Abandoned Mine Lands, October 1995, French Lick, IN.

Kepler, D.A., and E.C. McCleary. 1994. Successive alkalinity-producing systems (SAPS) for the treatment of acidic mine drainage. p. 195-204. In: Proceedings, International Land Reclamation and Mine Drainage Conference, April 24-29, 1994, USDI, Bureau of Mines SP 06A-94. Pittsburgh, PA.

Kepler, D.A., and E.C. McCleary. 1997. Passive aluminum treatment successes. In: Proceedings, Eighteenth West Virginia Surface Mine Drainage Task Force Symposium, April 15-16, 1997, Morgantown, WV.

Skousen, J., and P. Ziemkiewicz. 1996. Acid Mine Drainage Control and Treatment. National Mine Land Reclamation Center, West Virginia University, Morgantown, WV.

Watzlaf, G.R. 1997. Passive treatment of acid mine drainage in down-flow limestone systems. In: Proceedings, Fourteenth Annual Meeting of the American Society for Surface Mining and Reclamation, May 10-15, 1997, Austin, TX.

Wildeman, T., J. Gusek, and G. Brodie. 1993. Wetland design for mining operations. Bitech Publishers Ltd., Richmond, B.C.

Ziemkiewicz, P.F., J.G. Skousen, D.L. Brant, P.L. Sterner, and R.J. Lovett. 1997. Acid mine drainage treatment with armored limestone in open limestone channels. J. Environ. Qual. 26: 1017-1024.

Table 1. Design requirements and factors for passive treatment systems.

System Type	Requirements	Construction	Design Factors	References
Aerobic Wetland	Net alkaline water	Overland flow Cattails	10-20 g Fe/m /day 0.5-1 g Mn/m /day	Hedin et al. 1994
Anaerobic Wetland	Net acidic water Low flow	Flow over and within substrate	3.5 g acidity/m /day	Hedin et al. 1994 Wildeman et al. 1993 Eger 1994
Anoxic Limestone Drain	Net acidic water Low DO, Fe, Al	Flow through limestone	15 hrs residence time	Hedin and Watzlaf 1994
Successive Alkalinity Producing Systems	Net acidic water	Vertical flow	15-30 cm of organic matter 15 hrs residence time in LS	Kepler and McCleary 1997
Open Limestone Channel	Slope > 10%	Rock lined channel	Treatment is a function of acid load and residence time	Ziemkiewicz et al.
Limestone Leach Bed	Inflow pH < 3.0	Flow through limestone	1.5 hours residence time maintain pH < 3.0	
Slag Leach Bed	Metal free water	Flow through steel slag fines	1 to 3 hrs residence time	Ziemkiewicz et al.

Table 2. Construction costs, acid load treated and treatment costs for nine aerobic wetlands (AeW).

Site	Influent pH	Acid Load Treated (ton/yr)	Years in Service (years)	Construction Cost ($)	Estimated Service Life (years)	Efficiency ($/ton/yr)
WV-2a	6.7	11.6	4.0	5,432	20	23.4
WV-7a	6.8	14.3	3.0	13,552	20	47.4
OH-2c	6.0	1.1	1.0	1,334	20	61.0
WV-7b	6.5	7.4	3.0	12,712	20	85.9
WV-2b	7.2	0.4	4.0	4,116	20	514.5
WV-7c	6.6	0.7	3.0	15,484	20	1,106.0
WV-10a	2.5	0.4	1.0	12,093	20	1,512.0
AL-2d	5.0	0.0	4.0	5,500	na	na
MD-3d	5.5	-3.6	2.0	9,680	na	na

Table 3. Construction costs, acid load treated and treatment costs for 18 ponds.

Site	Influent pH	Acid Load Treated (ton/yr)	Years in Service (years)	Construction Cost ($)	Estimated Service Life (years)	Efficiency ($/ton/yr)
WV-2g	6.8	0.6	4.0	693	20	57.8
OH-2b	6.0	1.1	1.0	1,333	20	61.0
WV-10d	2.5	3.3	2.5	4,096	20	62.1
WV-30i	4.7	2.0	5.0	20,000	20	500.0
WV-15b	6.3	0.7	3.0	25,719	20	1,837.1
WV-15a	2.7	0.4	3.0	14,934	20	1,866.8
WV-30j	6.3	0.2	5.0	12,000	20	3,000.0
WV-16d	6.4	0.0	4.0	444	na	na
WV-16c	6.2	0.0	4.0	1,068	na	na
WV-2f	6.3	-0.3	4.0	693	na	na
MD-2c	4.5	-0.9	1.0	9,614	na	na
WV-12d	3.7	-0.9	2.0	1,068	na	na
WV-1e	6.3	-1.0	5.0	9,600	na	na
WV-10c	2.5	-1.4	2.5	7,508	na	na
MD-3b	4.5	-2.2	2.0	3,600	na	na
WV-30h	6.3	-2.4	5.0	14,070	na	na
MD-1b	4.0	-2.4	3.0	2,667	na	na
MD-2a	4.0	-2.6	1.0	2,600	na	na

Table 4. Construction costs, acid load treated and treatment costs for 18 anaerobic wetlands (AnW).

Site	Influent pH	Acid Load Treated (ton/yr)	Years in Service (years)	Construction Cost ($)	Estimated Service Life (years)	Efficiency ($/ton/yr)
WV-4b	5.9	35.4	4.0	97,925	20	138.3
WV-1g	2.9	10.2	5.0	53,333	20	261.4
WV-34	2.9	24.4	10.0	150,219	20	307.8
WV-35b	2.5	17.4	10.0	116,184	20	333.9
WV-30k	4.6	2.4	5.0	20,000	20	416.7
WV-30l	4.3	1.2	5.0	20,000	20	833.3
WV-6	3.0	31.3	7.0	549,901	20	878.4
WV-29	3.0	3.2	10.0	97,143	20	1,517.9
WV-25b	2.9	3.8	10.0	152,375	20	2,004.9
WV-1h	3.0	1.6	5.0	125,187	20	3,912.1
WV-16b	6.0	0.0	4.0	4,947	na	na
WV-25a	3.0	-0.5	10.0	100,000	na	na
WV-28d	5.8	-1.3	8.5	47,529	na	na
WV-22b	6.5	-1.4	5.0	4,983	na	na
WV-2d	6.7	-3.4	4.0	38,549	na	na
WV-2e	7.2	-5.7	4.0	14,026	na	na
WV-28c	5.7	-7.5	8.5	23,823	na	na
WV-1i	3.7	-160.6	5.0	43,965	na	na

Table 5. Construction costs, acid load treated and treatment costs for 38 anoxic limestone drains (ALD).

Site	Influent pH	Acid Load Treated (tons/yr)	Years in Service (years)	Construction Cost ($)	Estimated Service Life (years)	Efficiency ($/ton/yr)
WV-26	3.0	6.7	8.0	3,488	15	34.1
WV-30b	6.3	4.7	5.0	3,321	20	35.3
WV-32	2.9	8.0	4.0	5,747	20	35.9
WV-1a	3.7	130.9	5.0	115,207	20	44.0
OH-1c	2.9	20.1	2.0	18,154	20	45.0
WV-28b	3.1	15.1	8.5	2,656	3	58.6
WV-19a	3.3	19.5	3.0	26,301	20	67.4
WV-7e	4.1	125.6	3.0	169,695	20	67.6
WV-1b	3.7	121.4	5.0	167,994	20	69.2
WV-2c	4.1	29.4	4.0	42,743	20	72.7
WV-28a	3.0	4.6	8.5	6,829	20	74.2
WV-4a	2.9	7.1	4.0	11,041	20	77.8
WV-22a	2.7	11.0	5.0	17,299	20	78.6
WV-1d	3.7	8.8	5.0	13,957	20	79.3
MD-3a	4.0	13.2	5.0	20,790	20	79.0
WV-30g	2.9	5.1	5.0	8,505	20	83.4
WV-19b	3.3	10.3	3.0	19,050	20	92.5
WV-8a	3.5	17.8	4.5	34,208	20	96.1
WV-5	3.8	9.3	2.0	25,783	20	138.6
WV-30e	4.3	0.8	5.0	2,430	20	151.9
WV-30c	6.5	0.9	5.0	2,916	20	162.0
WV-23h	3.4	15.2	9.0	17,446	6	184.8
WV-30a	5.2	1.3	5.0	7,452	20	286.6
WV-8b	3.4	4.3	4.5	25,099	20	291.8
WV-23f	3.6	2.0	8.0	5,365	8	353.0
WV23a	3.8	2.1	8.0	12,298	16	357.5
WV-23b	3.1	8.9	9.0	18,876	6	357.5
WV-30d	6.3	0.3	5.0	2,969	20	494.8
WV-17	3.1	18.8	12.0	187,110	20	497.6
WV-35a	2.9	20.8	1.4	15,903	1	546.1
WV-7d	5.8	0.2	3.0	2,377	20	594.3
WV-23d	3.9	0.3	9.0	4,004	20	667.3
WV-1c	3.7	2.5	5.0	39,961	20	799.2
WV-16a	3.3	0.0	4.0	32,238	na	na
WV-23c	3.8	-0.1	9.0	2,574	na	na
WV-30f	6.1	-1.9	5.0	3,779	na	na
WV-23e	3.4	-2.7	9.0	4,290	na	na
WV-23a	5.1	-3.2	9.0	14,586	na	na

Table 6. Construction costs, acid load treated and treatment costs for four anoxic limestone drain - wetland combinations (ALD/W).

Site	Influent pH	Acid Load Treated (tons/yr)	Years in Service (years)	Construction Cost ($)	Estimated Service Life (years)	Efficiency ($/ton/yr)
WV-21	2.7	13.4	5.0	32,725	20	122.1
WV-20	2.3	19.3	6.0	81,325	20	210.7
WV-33b	3.9	0.5	5.0	4,033	20	403.3
WV-33a	5.9	0.0	5.0	3,797	20	9,492.5

Table 7. Construction costs, acid load treated and treatment costs for 19 vertical flow wetlands (VFW).

Site	Influent pH	Acid Load Treated (ton/yr)	Years in Service (years)	Construction Cost ($)	Estimated Service Life (years)	Efficiency ($/ton/yr)
MD-1c	4.0	21.8	3.0	16,880	20	39.0
KY-1	2.8	68.7	1.0	74,046	20	54.0
WV-3a	3.0	5.9	3.0	14,313	20	121.3
MD-1a	4.0	5.0	3.0	12,771	20	128.0
OH-1b	3.4	21.2	2.0	58,945	20	139.0
IN-1b	5.0	9.5	5.0	27,150	20	143.0
OH-2a	3.6	6.8	1.0	19,898	20	146.0
IN-1a	4.6	6.1	5.0	22,236	20	182.0
WV-3b	2.9	3.9	3.0	15,753	20	202.0
MD-2b	4.0	4.0	3.0	43,878	20	548.0
WV-15c	2.7	4.3	3.0	56,878	20	661.4
WV-7f	5.8	6.1	3.0	89,314	20	732.1
WV-3c	3.0	0.5	3.0	11,461	20	1,146.1
MD-3c	4.0	1.5	3.0	39,907	20	1,330.0
WV-1f	3.4	5.9	5.0	213,267	20	1,807.3
WV-15d	4.9	3.1	3.0	125,406	20	2,022.7
OH-2d	4.8	0.0	1.0	14,486	na	na
WV-16e	6.2	0.0	4.0	11,208	na	na
WV-7g	7.0	-97.2	3.0	101,868	na	na

Table 8. Construction costs, acid load treated and treatment costs for 11 open limestone channels (OLC).

Site	Influent pH	Acid Load Treated (tonnes/yr)	Years in Service (years)	Construction Cost ($)	Estimated Service Life (years)	Efficiency ($/tonne/yr)
IN-2b	4.8	13.2	2.0	950	3	24.0
WV-14	3.7	24.1	6.0	24,004	20	49.8
WV-24	4.0	19.4	2.0	46,272	20	119.3
WV-31	2.9	25.0	4.0	73,184	20	146.4
WV-36b	5.6	2.8	1.0	11,250	20	200.9
WV-36a	5.0	1.7	3.0	7,500	20	220.6
WV-11	2.5	6.8	2.5	36,192	20	266.1
WV-12c	4.2	5.0	2.0	28,099	20	281.0
WV-12b	3.5	2.8	2.0	31,590	20	564.1
WV-33c	5.1	0.1	5.0	15,046	20	7,523.0
WV-12a	3.5	-4.7	2.0	34,992	na	na

Table 9. Construction costs, acid load treated and treatment costs for 18 limestone beds (LSB).

Site	Influent pH	Acid Load Treated (ton/yr)	Years in Service (years)	Construction Cost ($)	Estimated Service Life (years)	Efficiency ($/ton/yr)
WV-36c	5.7	10.9	3.0	3,750	11	31.0
WV-13b	2.8	14.1	5.0	14,122	20	50.1
TN-1c	2.9	58.9	6.0	74,911	20	64.0
WV-13a	3.1	7.2	5.0	14,122	20	98.1
TN-1d	3.0	44.0	1.5	93,436	20	105.0
IN-2a	2.7	47.1	2.0	100,000	20	106.0
TN-2c	2.3	32.3	4.0	120,000	20	186.0
TN-1b	3.1	24.4	2.5	98,989	20	203.0
TN-2d	2.6	7.6	3.0	113,437	20	221.0
WV-9	3.3	2.2	4.0	10,350	20	235.2
TN-2b	2.5	24.1	6.0	113,783	20	236.0
AL-1	4.0	7.4	1.0	35,825	20	242.0
WV-36d	5.6	4.6	1.0	37,500	20	408.0
AL-2c	3.9	10.6	4.0	100,997	20	476.0
AL-2a	6.7	3.6	4.0	37,667	20	523.0
TN-1a	3.2	6.7	4.0	104,991	20	784.0
AL-2b	7.0	0.4	4.0	17,527	20	2,191.0
TN-2a	2.9	1.3	8.0	150,530	20	5,790.0

Table 10. Construction costs, acid load treated and treatment costs for two slag leach beds (SLB).

Site	Influent pH	Acid Load Treated (ton/yr)	Years in Service (years)	Construction Cost ($)	Estimated Service Life (years)	Efficiency ($/ton/yr)
OH-1a	3.7	313.6	2.0	77,239	20	12.0
WV-37	4.4	19.0	1.0	31,970	20	84.0

Table 11. Summary of the treatment effectiveness (positive vs negative) and cost (successful vs failure) of 137 passive treatment systems.

System Type	Number of Units	Average Total Cost	Average Acid Treated (tons/yr)	Percent With Positive Treatment	Percent Successful Treatment
SLB	2	$54,604	166.3	100%	100%
LSB	18	$68,997	17.1	100%	78%
ALD	38	$29,327	16.8	87%	76%
ALD/W	4	$30,468	8.3	100%	75%
OLC	11	$28,098	8.7	91%	73%
VFW	19	$51,035	4.1	84%	47%
AeW	9	$8,878	3.6	78%	44%
AnW	18	$92,227	-2.7	56%	28%
Ponds	18	$7,317	-0.3	39%	22%
Total:	137.0				