TREATMENT OF ACID MINE DRAINAGE BY PASSIVE TREATMENT SYSTEMS[1]

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Abstract: Passive acid mine drainage treatment systems constructed on sites in West Virginia treat flows ranging from 4 to 98 L/min (1 to 26 gpm) and acidity concentrations from 170 to 2,400 mg/L. Five wetland systems reduce acidity by 3% to 76%, and iron concentrations by 62% to 80%. These wetlands are generally much smaller in area than that recommended by earlier formulas based on iron loads, but they still show good amelioration of acid and iron loads. In two of the five wetlands, limestone was not incorporated in the substrate. Iron and acid reductions were similar between wetlands with and without limestone revealing that limestone may not be important for metal removal in wetlands. Anoxic limestone drains (ALDs) reduce acidity by 11% to 100%. Based on our successes and failures in building and monitoring ALDs, the following conclusions have been reached: (1) organic matter should **not** be placed in drains owing to microorganism growth on the limestone thereby reducing limestone dissolution, (2) amount of limestone (metric tons of limestone per metric tons of acid load per year) shows little correlation to effectiveness and acidity reductions, (3) larger limestone particle size (8 to 25 cm) should be included to maintain water flow through the drain especially when some aluminum, iron, and grit accumulate in the drain, (4) oxygen intrusion into the drain must be prevented, and (5) pipes installed in drains must be large in diameter with large perforations to reduce the chance for plugging.

Additional Key Words: acidity, alkalinity, aluminum, anoxic limestone drains, iron, manganese, wetlands

Introduction

Wetlands and anoxic limestone drains (ALDs) are passive treatment systems for acid mine drainage (AMD), and do not require continual addition of chemicals as active treatment systems do. Wetlands have been used for decades in the treatment of municipal wastewater (Water Pollution Control Federation 1990), but only within the last 10 yrs have they received serious attention in the treatment of AMD. Researchers at Wright State University and West Virginia University independently noted that AMD from abandoned mined lands was improved after passing through natural Sphagnum wetlands in Ohio and West Virginia (Huntsman et al. 1978, Wieder and Lang 1982). Since then, investigators have documented many other sites where the same phenomenon was observed (Brooks et al. 1985, Burris 1984, Samuel et al. 1988). Artificial wetlands have since been constructed by operators and researchers, and results have generally been positive.

The criteria for constructing AMD wetlands is variable since the mechanisms of alkalinity generation and metal removal are not entirely understood (Hedin and Nairn 1992). Generally, sizing is dependent on acidity and flows (acid load), with considerations for iron, manganese, and aluminum removal, and pH. Oxidation, hydrolysis, and precipitation reactions produce additional acidity which must be counteracted by alkalinity. Increasing buffering capacity (alkalinity) in wetlands is accomplished by installing an ALD and/or by encouraging sulfate reduction within the wetland. Sulfate reduction can generate up to 200 mg/L of sulfides, which are available for metal complexation (Rabenhorst et al. 1992). A low redox potential is required for this process. Factors such as climate, season, organic matter inputs, and nutrient availability can dramatically affect the amount of sulfide generation and subsequent metal decrease.

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ALDs have received much attention since their discovery recently (Brodie et al. 1990, Turner and McCoy 1990) because they have the potential to add alkalinity to mine water without biological or seasonal limitations. An ALD consists of limestone buried in a trench, underdrain, or cell that is protected from the influence of atmospheric or dissolved oxygen. Acid water is intercepted underground and directed through the drain, causing limestone dissolution and the generation of alkalinity without armoring the limestone. The conditioned water is then brought to the surface and, when exposed to oxygen, the metals in the water then precipitate more rapidly than when untreated by the ALD. ALDs require AMD that is free of dissolved oxygen and are more likely to produce long-term effectiveness when iron is largely in the ferrous state and aluminum concentrations are less than 50 mg/L (Nairn et al. 1990, Skousen 1991). The objective of this paper is to evaluate the use of several wetlands and ALDs in West Virginia for treating AMD. The evaluation will be based on acidity and metal removal of the treated versus the untreated water.

Materials and Methods

The passive systems reported in this paper were constructed during 1990 to 1992 by the West Virginia Division of Environmental Protection (WVDEP) Bond Forfeiture Program (table 1). The wetlands, Keister, S.Kelly, Pierce, and Z & F, were constructed in 1990. All ALDs were constructed in 1991 or 1992.

Each wetland system was designed specifically for the site resulting in variable total metal inputs per unit area of wetland. Average flows into each wetland vary from 98 L/m (26 gpm) at Pierce to 17 L/m (4 gpm) at Keister 1. Specific construction criteria for each wetland are discussed in the Results section. In general, 0.6 to 1 m (2 to 3 ft) of organic material composed of peat and hay overlie about 15 to 30 cm (6 in to 1 ft) of limestone in each of the wetlands. Hay bales were usually used as barriers to slow and direct the water through the wetland.

The majority of the ALDs were constructed with 10- to 20-mil plastic on the bottom, filter fabric placed inside the plastic surrounding #57 (gravel-sized) limestone, and hay bales placed on top of the limestone separated by the filter fabric. The plastic was then wrapped around the limestone and hay (specific drawings and construction criteria are available from the authors). A few ALDs were constructed differently. These different designs are detailed in the Results section.

Results

Inflow and outflow water quality are presented in table 2 and represent averages over approximately 3 yrs for the wetlands and 2 yrs for the ALDs. Acidity, alkalinity, iron, manganese, aluminum, and sulfate were the parameters chosen to indicate the effectiveness of the system in treating AMD.

Wetlands

Keister The Keister 1 wetland has a relatively low metal-load-to-area ratio (14.7 g per day per m^2 (gdm^2)) (table 3). It reduced the acidity of an average 17-L/m (4-gpm) flow from 252 to 59 mg/L (76% reduction) and increased pH from 3.1 to 5.4 (table 2). Iron was reduced from 23 to 9 mg/L (62%) (tables 2 and 4), while manganese was minimally reduced from 23 to 20 mg/L (11%). Aluminum was decreased on the average from 27 to 13 mg/L (52%).

The Keister 3/2 wetland has the smallest metal-load-to-area ratio (3.1 gdm^2). It reduced the acidity of a 19-L/m (5-gpm) flow from 106 to 56 mg/L (48%) and iron from 11 to 3 mg/L (73%), but did little to reduce manganese and aluminum concentrations (table 2). This site exhibits a low acid load into the wetland compared with the other wetland sites (table 3) but doesn't show any improved capacity of decreasing acid or iron concentrations due to the larger wetland area. The large capital cost ($225,000) of installing the Keister wetlands suggests that chemical treatment might have been cheaper (caustic soda cost of $8,500 per year or ammonia cost of $9,700 per year). The site is very remote, however, with poor access, and the intermittent flows make chemical treatment inefficient. Further, the receiving stream has not had to bear the wide fluctuations in pH that are common to chemical treatment systems with intermittent flows.

S.Kelly The S.Kelly wetland site differs from the earlier design by attempting to encourage subsurface flow under and through the organic strata. The flow was directed downward into the substrate by the use of a geotextile fabric placed under and on the upstream side of the hay bale barriers. The attempt to direct the flow was unsuccessful. Most of the flow appears to pass through and over the hay bale dikes, rather than under them.

This wetland system provided limited surface area for the amount of acid load (133.5 gdm^2) and iron load (10.1 gdm^2) (tables 3 and 4). Significant reductions in iron were found throughout the sampling period, with a 31-month average of 68% reduction (from 105 to 33 mg/L). Acidity generally increased through the system for the first fall and winter after construction, but has since continued to show improvements. Apparently, AMD seeps into the wetland from the bottom, as flows increase an average of 43% from influent to effluent. Due to this condition, it is more meaningful to compare preconstruction acid loads to postconstruction loads. In the 24-month period prior to construction of the system, an average of 56 L/m (14.8 gpm) with acidity of 2,432 mg/L left the site (196,116 g acid per day or 71 mt/yr). Since the system has been constructed, the average effluent flow has been 95 L/m (25.1 gpm) with acidity of 1366 mg/L (186,867 g acid per day or 68 mt/yr). The total acid load of this site has been reduced by only 5%, but the iron load has been reduced by over 69% (14,364 to 4,514 g per day). These reductions were accomplished without any vegetation in the wetland.

Pierce This wetland employs the "classic" approach to wetland construction. It uses surface flow over a limestone-enriched, organic substrate. It also provides a moderate acid-load-to-area ratio (20 gdm^2). The system has averaged about 52% removal of the acidity and about 80% of the iron with substantial seasonal variation. It has consistently removed a small percentage of aluminum (25%) and manganese (11%) except during large flow events.

Z & F Construction of this wetland employed organic substrates similar to those previously described, but encouraged subsurface flow by means of 6-in plastic pipes under earthen barriers. This wetland provided the highest iron-load-per-area ratio (19.2 gdm^2) but has reduced metals consistently since its construction over 36 months ago. Only a mild pH enhancement has been seen despite removal of 67% of the acidity. Much of the acidity reduction is associated with the removal of iron (77%) and perhaps aluminum (63%), while manganese has sometimes been decreased and sometimes increased through the system.

Removal of an average of 67% of the acid load could be viewed as removing a total of over 25.5 mt (28 st) of acid per year. To have accomplished this chemically, about $22,000 per year in caustic soda would have been necessary. Attendant labor and sludge handling costs associated with a caustic treatment system would have likely doubled this cost. The $110,000 construction cost appears to have been well worth the investment.

All the wetland systems exhibited seasonal variability with respect to acidity and metal removal efficiency. Generally, removal efficiencies increased during summer/fall and decreased during winter/spring. All but the Keister wetlands had about 23 cm of limestone at the base of the wetland. In all cases, the limestone was coated and covered by metal precipitates, and it appeared that acid water was not flowing through the limestone because of the metal covering. Therefore when the Keister wetlands were constructed, no limestone was incorporated in the substrate. Results show that the Keister wetlands without limestone are similar in acid and iron removal as wetlands with limestone. In future wetland designs in the WVDEP AMD treatment program, a layer of limestone will not be incorporated underneath the organic material.

Anoxic Limestone Drains

Greendale Most ALDs under this project were constructed at the Greendale site in 1991 (table 1). All ALDs generated substantial alkalinity for a few months, but some were overcome as acidity returned and alkalinity diminished. Fifteen of the 19 ALDs shown in table 1 reduced the total acid load by 50% or more. Generally, aluminum was retained in the drains. Iron and manganese left the drains in various amounts, but most postdrain concentrations were slightly lower than predrain concentrations (table 2). For example, the Greendale 11 postALD water showed a pH increase from 3.1 to 6.0, an increase of alkalinity, and slight iron, manganese, and aluminum reductions (table 2). This drain appears to be functioning with limestone dissolution and low metal retention in the drain. On the other hand, the 51 ALD raised pH from 2.8 to 3.4, reduced acidity by 41% (due to some metal retention in the drain), and slightly reduced iron, manganese, and aluminum. The drain does not generate much alkalinity and it may already be coated by metals from the water.

Kodiak An ALD and wetland were installed at this site, and acidity is reduced by 99%. However, iron, manganese, and aluminum are also retained in the drain which will cause the limestone drain to plug eventually. The use of an ALD at this site will be evaluated when water begins leaking out of the top of the drain.

Lillybrook A relatively high-pH (net alkaline), high-iron seep is being treated on this site. The water from the site joins other seepage and enters the existing sediment pond, which is completely full of sediment and supports a lush volunteer cattail population. A concrete septic tank was filled with limestone and installed at the site in November 1992. Alkalinity in the water has been increased substantially (23 to 259 mg/L) which should improve the metal removal efficiency of the existing wetland.

Preston An ALD and wetland treat a small flow of 13 L/m (3.5 gpm) with acidity of 775 mg/L and iron of 570 mg/L. Effluent water from the limestone cell has a pH of 6.0, acidity of 413 mg/L (47% reduction) and iron of 350 mg/L (40% reduction). Some iron and all aluminum are retained in the drain. The ALD-treated water then enters an aerobic wetland. At the exit of the wetland, the pH drops to 3.3, and acidity is reduced to 190 mg/L (76% reduction), and iron is further decreased to 20 mg/L (96% reduction).

Lobo Capital Two ALDs and small wetlands were installed at this site, but the landowner's activities have disrupted the function of the ALDs. The ALDs and wetlands caused a change from 470 mg/L acidity to 223 mg/L alkalinity, resulting in remarkable improvement in the quality of Glade Run, the receiving stream, for a few months (table 1). However, the drain was likely undersized hydraulically for the large flows. This problem was compounded by the presence of bacterial growth on the limestone in proximity to the hay.

Benham WVDEP has installed modified septic tanks at four locations at this site in an attempt to study ALD conditions without the difficulty of reexcavating earthen drains. In these systems, the limestone can be viewed by taking off the lid of the tank. Problems have arisen with differential settling and limestone plugging by ferric iron and grit. No data are presented in table 2 for this site.

Discussion

The most surprising finding in analyzing wetland water quality data is that limestone in wetland substrates did not appear to improve the wetlands metal removal efficiency. As more systems are constructed with and without limestone in the substrate, this finding may be substantiated and reasons may be clarified. In the wetland systems with limestone, the limestone became encrusted with metal precipitates. In fact, the metal crust was so hard that crowbars were needed to break the crust. This crust restricted the flow of water through the limestone, and eliminated the possibility of adding alkalinity to the water.

"Autopsies" of failed or poorly functioning ALDs in 1992 have been accomplished as additional trenches and wetlands were installed. It can now be said with certainty that hay should not be buried in proximity to the limestone in an ALD because it encourages the growth of organisms on the limestone, thereby reducing pore space and dissolution of the limestone. Where hay was not placed in the ALD, the limestone was clean. New ALDs were constructed without hay (originally hay was thought to serve as an oxygen sink and to promote CO_2 production through organic matter decomposition, and thereby to increase limestone dissolution), and also included larger stone (8 to 25 cm) placed at the bottom of the drain and collection zones. Substantial "grit" and metal precipitates were generated upon excavation, so measures must be taken to allow these to settle before contact with the finer limestone.

Monitoring of passive systems has led to the following general observations on ALD construction. **Organic Matter.** Addition of hay (even separated from limestone by geotextile fabric) leads to problems of limestone dissolution because of growth of microorganisms. Some builders have enjoyed undocumented success using chicken litter, however, ALDs constructed under the WVDEP program are not including organic matter in the drain.

Amounts and Grade of Limestone. High limestone-to-acid-load ratios are not an important factor in ALD success. While many of the WVDEP ALDs have been inhibited by metal and microorganism coatings of the limestone, large drains (those with greater than 20 mt of limestone per metric ton of acid load per year) have not shown improved success over those with a lower ratio (table 1). The reduction in acid load per metric ton of limestone is quite variable and does not correlate with this ratio. The grade of limestone (which varied between 70 to 90% calcium carbonate equivalent in our ALDs) did not appear to be critical to limestone dissolution rates and alkalinity generation, supporting the work of Watzlaf and Hedin (1993). More acidic water seems to increase limestone dissolution.

Stone Size and Configuration. Larger limestone particle size (8 to 25 cm) increases hydraulic conductivity and may reduce the potential of plugging with iron or aluminum hydroxides. Larger stone also provides settling space for grit and other settleable matter generated during construction. However, large limestone particle size has less surface area for water contact and alkalinity generation. Contact between limestone and water can also be regulated by residence time. From our experience, about 15 to 20 hrs residence time is required for maximum alkalinity generation under a specific AMD and limestone condition. There is increasing evidence that cells or beds of limestone totally inundated with water provide better water contact and alkalinity generation.

Protection from Oxygen. Where inadequate measures were taken to prevent oxygen intrusion, iron precipitation and limestone armoring were observed. Drains must be lined and secured so that oxygen is restricted and water entering the drain is low in oxygen content. If surface water is allowed to "leak" into the drain, the system will fail.

Pipes. Observations of precipitate deposition on pipe walls and at perforations suggest that larger pipes (15 to 25 cm) with larger perforations (2.5 cm or greater) promote longevity. The use of pipes in ALDs is being reduced because of the problems of plugging.

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Table 1. Flows and acid concentrations of passive treatment systems for treating AMD. System specifications include mt of limestone, mt of limestone per mt of acid, and materials used.

Site	Limestone mt	Flow L/m	Pre-Acid mg/L	Post-Acid mg/L	% Reduction	mt Limestone / mt Acid Load	Materials
Wetlands							
Keister 1	0	17	252	59	76	----	compost
Keister 3/2	0	19	106	56	47	----	compost
S.Kelly	780	95	1,383	1,366	3	----	LS,compost,no plts
Pierce	450	98	118	57	52	----	LS, compost
Z & F	476	30	2,388	801	67	----	LS, compost
ALDs							
Greendale							
11	51	45	195	90	54	2.0	hay, #57
21	66	6	700	0	100	10.6	hay, #57
41	18	6	280	140	50	6.6	#57
42	21	19	290	100	66	6.4	hay, #57
43	43	68	600	70	88	1.8	hay, #57
44	36	19	280	220	11	10.0	#57
51	8	4	1,020	600	41	3.7	hay, #57
52	14	7	700	350	50	5.8	hay, #57
61	22	19	2,000	1,000	50	1.0	15-25 cm, #57
101	9	11	1,200	600	50	1.1	#57
102	14	19	600	310	49	3.1	15-25 cm
103	61	15	266	145	45	27.3	hay, #57
108	34	23	370	80	78	7.1	hay, #57
121	19	7	800	0	100	8.5	15-25 cm
131	15	4	750	30	96	45.0	hay, #57
Kodiak	128	15	2,210	30	99	6.6	8-12 cm, #4
Lillybrook	7	60	170	-259	100	12.5	#57
Preston	90	13	775	105	86	12.8	#57
Lobo Cap	250	87	470	-123	100	10.4	hay, #57

Table 2. Characteristics of AMD before and after passing through passive systems in WV.

Site	Flow L/m	pH		Acid mg/L		Alkal mg/L		Fe mg/L		Mn mg/L		Al mg/L		SO_4 mg/L	
		In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Wetlands															
Keistr 1	17	3.1	5.4	252	59	--	---	23	9	23	20	27	13	673	466
Keistr 3/2	19	4.0	4.8	106	56	--	---	11	3	11	11	10	8	356	347
S.Kelly	95	2.9	3.1	1,383	1,366	--	---	105	33	51	50	157	163	2,558	2,660
Pierce	98	3.3	4.4	118	57	--	---	10	2	8	7	9	7	217	227
Z & F	30	2.5	3.5	2,388	801	--	---	376	86	51	40	206	76	2,821	1,662
ALDs															
Greendale															
11	45	3.1	6.0	195	90	0	30	130	110	24	19	3	0	300	500
21	6	2.9	5.7	700	0	0	160	190	160	160	80	28	0	1,900	1,400
41	6	2.6	6.1	280	140	0	30	160	140	40	50	4	0	1,000	1,000
42	19	3.1	6.4	290	100	0	100	22	70	95	90	24	0	1,000	1,400
43	68	2.9	6.2	600	70	0	75	120	110	90	50	80	0	1,800	900
44	19	3.1	5.6	280	220	0	25	210	150	95	50	24	0	1,100	1,100
51	4	2.8	3.4	1,020	600	0	0	140	130	200	160	100	70	2,400	2,000
52	7	2.8	4.7	700	350	0	1	130	100	170	130	55	30	1,600	1,600
61	19	2.8	4.3	2,000	1,000	0	0	300	360	140	140	140	100	3,000	2,000
101	11	2.6	4.8	1,200	600	0	6	150	300	140	120	70	10	2,300	2,000
102	19	2.8	3.7	600	310	0	0	300	100	120	90	94	17	2,060	1,500
103	15	2.8	6.1	266	145	0	80	300	210	120	90	94	0	2,100	1,500
108	23	2.9	6.0	370	80	0	50	80	80	105	96	9	1	1,300	1,300
121	7	3.0	6.8	800	0	0	340	30	30	45	12	50	0	1,100	600
131	4	3.1	6.1	750	30	0	80	41	10	160	140	88	2	2,660	2,000
Kodiak	15	2.8	4.3	2,210	30	0	0	124	1	45	2	287	3	2,900	140
Lillybrook	60	5.7	6.4	170	0	23	259	60	43	21	21	0	0	101	45
Preston	13	3.5	6.1	775	413	0	308	570	350	12	12	50	1	1,330	1,330
Lobo Cap	87	2.9	6.2	470	9	0	131	96	58	3	4	18	0	780	575

Table 3. Reduction of acidity and efficiency of five wetlands for treating acid mine drainage. Flows and chemistry from table 2 were used to calculate acid loads.

Site	Area m^2	Recommend[1] m^2	Load in[2] g/day	Load out g/day	Removal %	Load/Area gdm^2
Keister 1	408	859	6,015	1,413	76%	14.7
Keister 3/2	929	371	2,885	1,524	47%	3.1
S.Kelly	1,417	27,027	189,187	186,629	3%	133.5
Pierce	813	2,343	16,378	7,912	52%	20.1
Z & F	863	15,060	105,287	35,316	67%	122.0

[1]Recommended m^2 by U.S. Bureau of Mines for net acid mine drainage.
m^2 = acid load (g/d)/7.

[2]Loads were calculated by L/m x mg/L x 1.44 = g/day.

Table 4. Removal of iron and efficiency of five wetlands in treating acid mine drainage. Loads were calculated from data in table 2.

Site	Area m^2	Load in g/day	Load out g/day	Removal %	Load/Area gdm^2
Keister 1	408	549	215	62%	1.3
Keister 3/2	929	299	82	73%	0.3
S.Kelly	1,417	14,345	4,509	68%	10.1
Pierce	813	1,388	278	80%	1.7
Z & F	863	16,578	3,792	77%	19.2