PERFORMANCE OF 116 PASSIVE TREATMENT SYSTEMS FOR ACID MINE DRAINAGE[1]

Jeff Skousen[2] and Paul Ziemkiewicz[3]

Abstract. State and federal reclamation programs, mining operators, and citizen-based watershed organizations have constructed hundreds of passive systems in the eastern United States over the past 20 years to provide reliable, low cost, low maintenance mine water treatment in remote locations. In 2000, we evaluated 116 systems comprised of eight system types in eight states. We revisited 14 of these sites in 2004 to confirm results from the earlier study. Each system was monitored for influent and effluent flow, pH, net acidity, and metal concentrations. Performance was normalized among types by calculating acid load removed, and also by converting construction cost, projected service life, and metric tonnes of acid load treated into cost per tonne of acid treated. Of the 116 systems, 105 reduced acid load (90%). Average acid load reductions were 0.8 t/yr for Ponds; about 9 t/yr for open limestone channels (OLC), anaerobic wetlands (AnW), aerobic wetlands (AeW), and vertical flow wetlands (VFW); 76 t/yr for slag leach beds (SLB), and about 15 t/yr for limestone leach beds (LSB) and anoxic limestone drains (ALD). Average removal rates ranged from 18 to 2,334 g/day/t for the limestone systems, and 1.7 to 87 $g/m^2/day$ for the Ponds and wetlands. Average costs for acid removal varied from $36/t/yr for SLB to $1,468/t/yr for Ponds. The 2004 data showed slightly greater removal efficiencies for two Ponds, two VFWs, and one LSB. Large declines in removal were found for one AnW, two VFWs, one ALD, and one OLC. Two OLCs greatly increased efficiency. Most passive systems were effective for >5 yrs, yet there was wide variation in performance within each system type.

Additional Key words: acidity; acid load; aerobic wetlands; anaerobic wetlands; anoxic limestone drains; limestone leach beds; open limestone channels; Ponds, slag leach beds; successive alkalinity producing systems; vertical flow wetlands.

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[1] Paper was presented at the 2005 National Meeting of the American Society of Mining and Reclamation, Breckenridge CO, June, 19-23 2005. Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

[2]Jeff Skousen, Division of Plant and Soil Sciences and Paul Ziemkiewicz, National Mine Land Reclamation Center; West Virginia University, Morgantown, WV; e-mail: jskousen@wvu.edu

Introduction

Approximately 20,000 km of streams and rivers in the eastern United States are degraded by AMD with more than 80% coming from abandoned underground coal workings (U.S. Environmental Protection Agency 1995). Since no company or individual claims responsibility for reclaiming abandoned mine lands, the treatment of any AMD source or stream becomes a public responsibility and expense. When AMD is neutralized, its dissolved metals precipitate as low density flocculates (floc or sludge) of metal hydroxy-sulfates (Nordstrom 1982; Sterner et al. 1998; Thomas and Romanek 2002). Therefore, most AMD treatment systems involve alkalinity addition and metal precipitation. Treatment systems fall into two categories: active and passive. Active or chemical treatment systems generally involve dosing of the AMD with an alkaline reagent such as lime, caustic soda, soda ash, or ammonia, and collecting the floc in Ponds. Several reports are available that consider the site requirements, types of water, and costs for treating AMD with such chemicals (Environmental Protection Agency 1983; Skousen and Ziemkiewicz 1996; Skousen et al. 2000). Such systems require access and regular maintenance to sustain chemical supplies, power, pumps, and the floc handling system. These systems are reliable and effective if regularly controlled and maintained, but their cost, power and maintenance requirements make them impractical for most remote, abandoned mines.

Over the past 25 years, a variety of passive treatment systems have been developed that do not require continuous chemical inputs because they are based on naturally-occurring chemical and biological processes (Hedin et al. 1994a). The primary passive treatment technologies include aerobic (AeW) and anaerobic wetlands (AnW), sulfate reducing bioreactors, anoxic limestone drains (ALD), vertical flow wetlands (VFW, sometimes referred to as successive alkalinity producing systems, or SAPS), limestone leach beds (LSB), slag leach beds (SLB), and open limestone channels (OLC).

Selection and design of an effective passive system is based on water chemistry, flow rate, local topography, and site characteristics (Hedin et al. 1994a; Hyman and Watzlaf 1995; Skousen et al. 1998; Younger 2000). Fig. 1 summarizes current thinking on the selection of passive systems for various conditions and Table 1 lists characteristics, design considerations, and sizing factors. In general, Ponds and AeW can treat net alkaline water by allowing the water to reside in the structure long enough for metals to precipitate. Ponds and AeW are differentiated by plants being planted in the normally shallower AeW compared to Ponds. The ALDs can treat net acidic water with low Al, Fe^{3+}, and dissolved O_2 concentrations. Vertical flow wetlands, AnW, LSB, SLB, and OLCs can treat net acidic water with higher Al, Fe^{3+}, and DO, as well as net alkaline water.

Huntsman et al. (1978) and Wieder and Lang (1982) first noted amelioration of AMD following passage through naturally occurring Sphagnum bogs in Ohio and West Virginia. Studies by Brooks et al. (1985), Samuel et al. (1988), and Sencindiver and Bhumbla (1988) have documented similar phenomena in Typha wetlands. Numerous wetlands have since been constructed to receive AMD from both active and abandoned mine lands. Mechanisms of Fe, Mn, and Al retention within wetlands, listed in their approximate order of importance, include: 1) formation and precipitation of metal hydroxides, 2) microbial sulfate reduction and formation of metal sulfides, 3) organic complexation reactions, 4) exchange with other cations on negatively-charged sites, and 5) direct uptake by living plants (Calabrese et al. 1991; Kleinmann 1991).

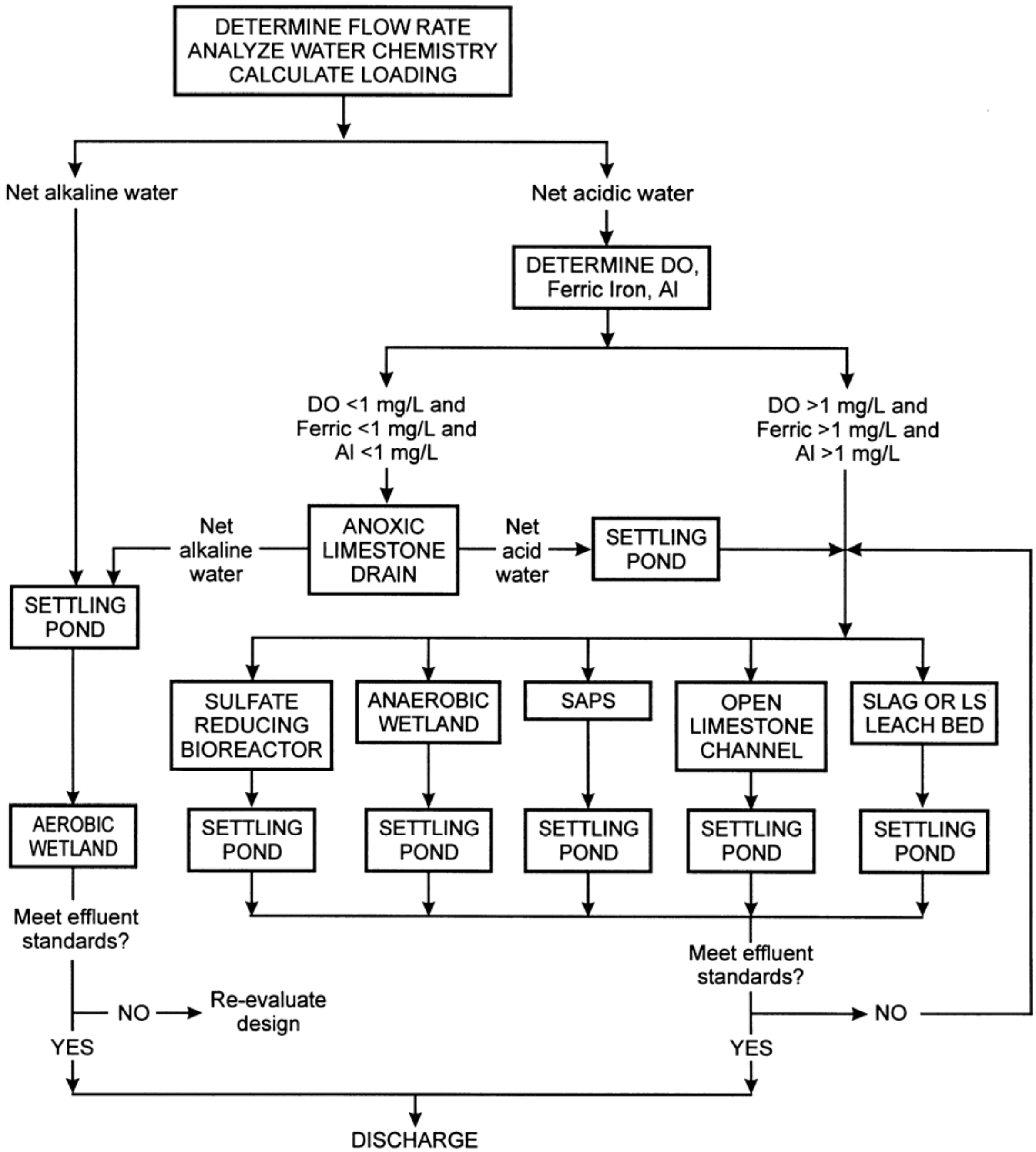

Figure 1. Passive system flow chart for design purposes.

Table 1. Water quality requirements and design factors for eight passive treatment system types.

System Type	Requirements	Construction	Design Factors	References
Ponds	Net alkaline water	Retention time for settling precip.	None	
Aerobic Wetland (AeW)	Net alkaline water	Overland flow Plant with Cattails	10-20 g Fe/m^2/day 0.5-1 g Mn/m^2/day	Hedin et al. 1994a
Anaerobic Wetland (AnW)	Net acidic water Low flow	Flow over and within substrate	3.5 g acidity/m^2/day	Hedin et al. 1994a Wildeman et al. 1993 Eger 1994 Watzlaf et al. 2000
Sulfate Reducing Bioreactor	Net acidic water Low flow	Flow through substrate	24 hrs residence time	Wildeman et al. 1993
Anoxic Limestone Drain (ALD)	Net acidic water Low DO, Fe, Al	Flow through buried limestone	15 hrs residence time	Hedin et al. 1994a
Vertical Flow Wetland (VFW)	Net acidic water	Vertical flow	15-30 cm of organic matter 15 hrs residence time in LS 20 g acidity/m^2/day	Kepler and McCleary 1994 Kepler and McCleary 1997 Watzlaf et al. 2000
Open Limestone Channel (OLC)	Slope > 10%	Rock lined channel	Acid load and residence Time	Ziemkiewicz et al. 1997
Limestone Leach Bed (LSB)	Inflow pH < 3.0	Flow through limestone	1.5 hours residence time	Black et al. 1999
Slag Leach Bed (SLB)	Metal free water	Flow through steel slag fines	1 to 3 hrs residence time	Simmons et al. 2002

Wetlands are divided into two strategies for AMD treatment: 1) oxidizing or aerobic wetlands consist of Typha and other wetland vegetation planted in shallow (<30 cm) sediments; and 2) reducing or anaerobic wetlands consist of Typha and other wetland vegetation planted in deep (>30 cm), organic substrates. Both types often use limestone as a base or the limestone may be mixed with the substrate.

Aerobic wetlands are designed to provide sufficient residence time to allow metal oxidation and hydrolysis, thereby causing precipitation and physical retention of Fe, Al, and Mn hydroxides. Wetland plants, such as Typha, Juncus, and Scirpus sp., encourage more uniform flow, help stabilize the substrate, help maintain microbial populations, and provide aesthetic qualities to the wetland. Brodie (1993) reported that wetlands receiving net alkaline AMD (pH range of 4.5-6.3, Fe 70 mg/L, Mn 17 mg/L, Al 30 mg/L,) were capable of removing the metals effectively to discharge standards. Hedin et al. (1994a) indicated that wetlands receiving net alkaline water can be sized using 10 to 20 $g/m^2/day$ for Fe and 0.5 to 1 $g/m^2/day$ for Mn. Duggan et al. (1992) found in bench-scale tests that Mn could be removed at rates of about 0.2 $g/m^2/day$ using Cladophora, an algae, in a limestone-lined basin.

Hellier et al. (1994) suggested that constructed wetlands are suitable for treating many post-mining ground water seeps of pH >5. However, sites with net acidic discharges have much lower treatment efficiency. For example, the Rougeux #1 site had a flow of 20 L/min and influent chemistry of 2.9 pH, 445 mg/L acidity, Fe 45 mg/L, Mn 70 mg/L, and Al 24 mg/L. After flowing through a two-celled aerobic wetland, Hellier (1997) found that pH increased from 2.9 to 3.2, acidity decreased by 43%, Fe by 50%, Mn by 17%, and Al by 83%. The wetland cost about $\$15/m^2$ to build in 1992 and was severely undersized.

Anaerobic wetlands rely on organic-rich substrates to generate reducing conditions, and also contain limestone for acid neutralization. These systems are used when the water is net acid and alkalinity is generated through sulfate reduction (Tuttle et al. 1969; Widdell 1988; Hedin and Nairn 1990; McIntyre and Edenborn 1990; Bolis et al. 1991; Eger 1992; Gusek 1998) and limestone dissolution (Brodie et al. 1990). Limestone dissolution and the metabolic products of sulfate-reducing bacteria raise pH and precipitate metals as sulfides, hydroxides and/or carbonates (Henrot and Wieder 1990). Five anaerobic wetlands in WV (Faulkner and Skousen 1994) receiving 4-98 L/min of net acid water (110-2400 mg/L acidity) reduced acidity by 3-76% and Fe concentrations by 62-80%. Similar results have been obtained in Kentucky (Karathanasis and Barton 1997), Pennsylvania (Hellier 1996; Rose et al. 2001), Ohio (Stark et al. 1994), and Tennessee (Schmidt and Sterns 2001). Hedin et al. (1994a) suggest that anaerobic wetlands can be sized using a factor of 3.5 g of $acidity/m^2/day$ for net acidic waters.

Sulfate reducing bioreactors are similar to anaerobic wetlands, where the acidic drainage is drawn through or flows through organic materials. The organic material hosts microorganisms that help in oxidation and reduction reactions (Wildeman et al. 1993). While most systems are quite small and may often be in barrels or tanks in series, others are very large. Gusek (1998) reports successfully treating flows from 4 to 4,800 L/min with moderate to high acidity water. Design criteria are usually based on a volume-loading factor that assumed 0.3 moles of sulfide per cubic meter per day would be generated. Adjustments were then made to the flow rate so that <0.3 moles of heavy metals per day would flow into the substrate (Wildeman et al. 1993).

Anoxic limestone drains (ALDs) are buried and sealed cells of limestone into which anoxic water is introduced. The limestone dissolves in AMD, and since CO_2 cannot escape, a buildup of bicarbonate occurs, thus adding alkalinity (Watzlaf and Hedin 1993). The effluent pH of a properly functioning ALD is around 6.3 and, at this pH, ferrous hydroxide will not precipitate. Ferric hydroxide and aluminum hydroxide will precipitate at this pH, however, and therefore it is important that ALDs only be installed to treat AMD that contains virtually no O_2, Fe^{3+}, or Al^{3+}. Metal hydroxide precipitation within an ALD will retard water flow, leading to premature failure due to plugging. ALDs were first described by Turner and McCoy (1990), and Brodie et al. (1990) found that ALDs helped pre-treat acid water for wetlands. Faulkner and Skousen (1995) reported both successes and failures among 11 ALDs treating mine water in WV. In all cases, pH was raised after ALD treatment, but three of the sites had pH values <5.0, indicating that the ALDs were not fully functioning or that the acid concentrations and retention times were too low for effective treatment. Acidity of water in these WV drains, varying from 170-2200 mg/L, decreased 50-80%, but Fe and Al concentrations in the outflow also decreased, indicating that Fe^{3+} and Al^{3+} hydroxides were precipitating inside the drains. At the Howe Bridge and Morrison ALDs, alkalinity increased by 128 and 248 mg/L, respectively, CO_2 pressures were near 0.1 atm, and calcite was at about 10% of saturation (Hedin et al. 1994a). For the past 8 years, the effluent from the ALD-wetland system at Morrison has always met effluent criteria (pH 6-9, and Fe <3 mg/L). At Howe Bridge, the ALD-wetland system has removed an average of 70% of the Fe over the past 7 years (Hedin et al. 1994a).

Hedin et al. (1994b) measured alkalinity output from 21 ALDs and found that the maximum value was 469 mg/L with values commonly between 150 and 300 mg/L. The level varied with water chemistry, CO_2 pressure, and contact time (Watzlaf and Hedin 1993). Watzlaf and Hedin suggested that contact times of 15 hr were optimal for alkalinity generation. In sizing an ALD, the amount of limestone that will dissolve during the design life must also be taken into account. Based on experiments with limestones of differing purity, Watzlaf and Hedin (1993) showed that >82% purity gave the highest performance. Like wetlands, ALDs may be a solution for treating specific types of AMD for a finite period, after which the system must be replenished or replaced.

In a vertical flow wetland (VFW), water flows downward through a layer of organic matter, then through a bed of limestone before flowing out through a drainage system (Kepler and McCleary 1994). The system is designed to reduce ferric to ferrous iron and to scavenge dissolved oxygen as the AMD passes through the organic matter. Sulfate reduction and Fe sulfide precipitation can also occur in the organic layer. This anoxic water is then introduced to an anaerobic limestone bed underneath the organic layer. In a typical VFW, acid water is ponded from 1-3 m over 0.1-0.3 m of organic compost, which is underlain by 0.5-1 m of limestone. A series of drainage pipes below the limestone conveys the water into an aerobic pond where ferrous iron oxidizes and is precipitated. Vertical flow wetlands can be placed in series with oxidizing Ponds to achieve desired water quality.

Kepler and McCleary (1994) found the Howe Bridge VFW reduced acidity from 320 to 93 mg/L and removed 2 mg/L ferric iron. At the Bark Camp site in PA, a VFW was employed to treat AMD with a pH of 4.3, acidity of 162 mg/L as $CaCO_3$, Fe of 60 mg/L, Mn of 10 mg/L, and Al of 5 mg/L (Hellier 1996). After passage through the VFW, the effluent had a pH of 7.1, Fe of 3 mg/L, Mn of 10 mg/L, and Al of <1 mg/L. The system effectively increased alkalinity, but retained most of the Fe and Al inside the system. Kepler and McCleary (1997) noted that Al precipitates could be flushed from VFW's, and cited a VFW that, with regular flushing, treated AMD containing 41 mg/L Al (see also Vinci and Schmidt 2001). Successful VFWs have used mushroom compost, while some other types of organic material have problems with plugging (Nairn et al. 2000; Demchak et al. 2001; Gusek and Wildeman 2002), and sizing has been based on acid removal at a rate of 20 $g/m^2/day$ (Watzlaf et al. 2000). Design variables such as composition and thickness of organic matter, limestone bed thickness, number and location of drainage pipes, and maintenance are under investigation (Jage et al. 2001; Rose and Dietz 2002; Watzlaf et al. 2002).

Limestone leach beds (LSB) consist of a pond constructed to receive water that has little or no alkalinity or dissolved metals (Black et al. 1999). The pond is filled with limestone, and designed with a retention time of at least 12 hours. Water alkalinity in such an open structure can reach 75 mg/L and can buffer streams against acidity introductions downstream. If the limestone is exhausted by dissolution, then more limestone can be added to the pond. In slag leach beds (SLB), a bed of steel slag fines (-1/8 in.) is used to treat water containing no Fe, Mn, or Al (Simmons et al. 2002). Steel slag has a much greater potential for generating alkalinity (up to 2,000 mg/L). Limestone or slag leach beds are attractive because they are easy to construct and replenish.

Open limestone channels (OLCs) are open channels or ditches lined with limestone (Ziemkiewicz et al. 1997). Past assumptions held that armored limestone (limestone covered or coated with Fe or Al hydroxides) ceased to dissolve, but experiments showed that coated limestone continues to dissolve at about 20 to 50% of the rates of unarmored limestone (Pearson and McDonnell 1975, Ziemkiewicz et al. 1994), though continued dissolution probably depends on pH, thickness of coating, and other variables. The length of the channel and the channel gradient, which affects turbulence and the buildup of coatings, are design factors that can be varied. Optimal performance is attained on slopes exceeding 12%, where flow velocities keep precipitates in suspension and where suspended sediments help clean precipitates from limestone surfaces. Open limestone channels can be used alone or in combination with other passive treatment systems. Residence time is critical to OLC performance, yet water velocity must remain high. Ziemkiewicz et al. (1997) found armored limestone in OLC's reduced acidity between 10 to 60%. The highest removal rates were with channels on slopes of 45-60% and for AMD with acidity of 500-2600 mg/L as $CaCO_3$. Three OLCs caused 60% removal of acidity and a 66% decrease in Fe (Ziemkiewicz and Brant 1996). At the Brandy Camp site in PA (Hellier 1997), an OLC removed 69% of the acidity, 72% of the Fe, and about 20% of the Mn and Al from the water.

The objective of this study was to evaluate the performance of a variety of passive treatment system types, and to assess their acid removal efficiency and cost effectiveness. We conducted a study in 2000 where 116 systems were sampled and evaluated for their performance. In 2004, we revisited 14 of those sites to determine if performance had changed over those four years.

Materials and Methods

Forty-nine sites with 116 separate treatment system types were chosen throughout the eastern U.S. (Alabama, Indiana, Kentucky, Maryland, Ohio, Tennessee, and West Virginia). The treatment units were between 2 and 12 years old in 2000. Four years later (2004), 14 of these sites were re-sampled. Data collected by state agencies were used to supplement data collected during the project so that sampling periods and water treatment assessments included several years. Information on the design, construction, and cost of each system was gathered from agencies and water quality data was collected for each site. Flows were measured by a bucket and stopwatch, weirs, or by flow meters. Water samples were analyzed for chemistry by certified laboratories for pH, acidity and alkalinity, and metal concentrations. By measuring flow and chemistry in and out of each system type, the amount of acid removed by each system type could be evaluated. Average net acidity concentrations both in and out are combined with flows to compute acid load treated.

For some treatment system types, however, it was not possible to directly measure incoming and outgoing water from a given treatment unit. For example, ALDs generally did not allow measurement of influent flow and acidity since they were built to capture and route the incoming AMD below the surface. In these cases, we relied on water quality and quantity data gathered before the system was installed, which was clearly of lower reliability. In data tables, the number of sampling times (N) is given, which provides the reader with the number of samples used to calculate the average flow (L/sec), and average influent and effluent pH and acidity concentrations. Acid load treated was calculated as the difference between average influent and effluent acid load (flow x net acidity concentrations). Removal efficiencies were calculated by dividing acid load treated (t/yr) by the size of the treatment system (g/m2/day for Ponds, AeW, AnW, and VFW). Removal efficiencies were calculated for limestone systems by dividing acid load treated (t/yr) by limestone mass (g/day/t). Residence time of water was calculated for ALDs and LSBs based on limestone mass, 50% porosity and flow into the system.

Analysis of the data depended on estimating three key parameters: acid load treated, unit construction cost, and service life. Acid load treated in a system was estimated as described above. The construction cost of each system was determined based on a set of accepted standard rates for building passive systems. These rates were \$3.25/m^3 for excavation, \$27/t of limestone, \$27/t of slag, and \$27/m^3 of organic matter (Charlie Miller, West Virginia Dept of Environmental Protection, personal communication). Treatment unit dimensions were available, so we calculated these costs to determine cost efficiency. This provided a constant basis for comparing the cost per metric tonne of acid removed for each treatment unit.

Service life is the expected period of performance for a given treatment unit. To normalize the data to provide a basis for comparison, we assigned a maximum service life of 20 years to all treatment units since this is a commonly accepted lifespan for passive system designs.

Efficiency was calculated in two ways: by cost and by removal. Cost efficiency was based on the cost to treat a tonne of acid per year (\$/t/yr), while removal efficiency was based on system size and acid load reduction.

Performance data were confounded to various degrees by several factors. First, there may have been a poor fit of the system type to the site and water conditions. These systems were some of the earliest of their type as designed and installed, and not much design criteria were available. For example, an ALD may have been constructed to treat water with higher than optimal Al concentrations, which would compromise the system's performance, but perhaps the designers were interested in understanding the rate at which aluminum would plug the system. Other examples include installing an OLC on moderately sloping ground, infrequent 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 system type. Our analysis did not account for such factors. Second, pre-construction estimates of incoming water flow and chemistry may not reflect actual current inflows. Therefore, poor performance could have resulted from under-sizing, which decreased residence time or provided greater acid or metal loads. Unfortunately, our evaluation methodology would simply show a reduced effectiveness for that treatment system without regard for misapplications, poor designs, or faulty water flow or chemistry.

Results

Ponds

The 11 Ponds (Table 2) were generally designed to capture and retain water to allow for metal oxidation, hydrolysis, and precipitation. Since metal ion oxidation and hydrolysis generates acidity, it was expected that many of the Ponds might be net acid producers. Nevertheless, only two did not remove acidity. Of the nine that did, seven reduced the acid load only slightly, and two showed good removal (WV-30i and WV-12d). The flow at WV-30i was very low, which allowed the acid water a long residence time for oxidation and metal and sediment settling. The WV-12d site showed high removal efficiency of 9.5 $g/m^2/day$ even when the influent pH was 3.7. This 12d Pond was placed right below a series of seeps and was used as a collection pond. Therefore, this water was highly unstable and upon collection the iron oxidized and began to precipitate without alkalinity addition at pH 2.7. Ponds or open flumes may show real benefits for decreasing acidity when oxidation and precipitation of iron at low pH can be accomplished (Hilton 2005). The acid treatment costs for these systems were between $16 and $3,754/t/yr.

Aerobic Wetlands

The performance of the six aerobic wetlands was highly variable. They removed between 0.1 and 27 t/yr of acid at costs ranging from $23 to >$7,000/t/yr over the expected 20-year lifetime (Table 3). These wetlands often received treated water that had passed through an ALD or VFW, and as such the influents for all but one had >6 pH and net alkaline water. All of them reduced the acid load by precipitating metals. For treatment, optimal aerobic wetland performance is expected when the pH is 6.0 or above and when the water is net alkaline. Even the WV-10a wetland reduced the acid load, despite the influent water pH being 2.5 with high acid concentrations. The 10a system collected water from seepage along the hillside, so oxidation reactions were occurring and causing iron to precipitate at low pH.

Table 2. Influent and effluent characteristics, acid load treated, construction costs and efficiencies for Ponds.

Site	N	Flow (L/s)	pH In	pH Out	Net Acidity In (mg/L)	Net Acidity Out (mg/L)	Acid Load Treated (t/yr)	Size (m^2)	Years in Service (yrs)	Construction Cost ($)	Service Life (yrs)	Removal Efficiency (g/m^2/day)	Cost Efficiency ($/t/yr)
WV-10d	11	0.8	5.9	6.0	-14	-14	0	558	3	4,096	20	0	0
WV-30j	7	0.3	6.3	6.3	14	22	0	1,040	5	12,000	20	0	0
WV-12d	9	0.5	3.7	3.9	604	411	3.4	892	2	1,068	20	9.5	16
WV-2g	11	0.1	6.8	7.1	127	-74	0.7	591	4	693	20	2.9	50
WV-2f	12	2.3	6.3	6.5	-53	-55	0.2	591	4	693	20	0.8	173
WV-30i	7	0.3	4.7	6.0	196	-32	2.5	1,930	5	20,000	20	3.2	400
WV-1e	7	0.6	6.3	6.6	-162	-177	0.3	4,091	5	9,600	20	0.2	1,600
WV-15b	18	0.4	4.5	5.0	185	134	0.7	2,151	3	25,719	20	0.8	1,837
WV-15a	18	0.4	2.7	2.8	528	499	0.4	1,561	3	14,934	20	0.6	1,867
WV-30h	7	0.1	6.3	6.4	117	81	0.2	1,150	5	14,070	20	0.4	3,517
WV-10c	11	0.8	5.5	5.9	-8	-9	0.1	305	3	7,508	20	0.8	3,754

Table 3. Influent and effluent characteristics, acid load treated, construction costs and efficiencies for Aerobic Wetlands (AeW).

Site	N	Flow (L/s)	pH In	pH Out	Net Acidity In (mg/L)	Net Acidity Out (mg/L)	Acid Load Treated (t/yr)	Size (m^2)	Years in Service (yrs)	Construction Cost ($)	Service Life (yrs)	Removal Efficiency (g/m^2/day)	Cost Efficiency ($/t/yr)
WV-2a	11	2.3	6.7	7.2	-55	-200	11.6	1,952	4	5,432	20	14.8	23
WV-7b	9	25.8	6.5	6.7	-105	-135	27.0	1,376	3	12,712	20	48.8	24
WV-7a	10	24.6	6.8	6.8	-135	-151	13.8	1,464	3	13,552	20	23.4	49
WV-2b	12	0.1	7.2	7.5	-74	-219	0.5	1,478	4	4,116	20	0.8	412
WV-10a	8	0.9	2.5	2.7	1664	1620	1.4	348	1	12,093	20	9.3	432
WV-7c	9	0.7	6.6	6.7	-237	-240	0.1	1,673	3	15,484	20	0.2	7,742

Surprisingly, the three AeWs with the highest and lowest removal efficiencies were from the same site. The WV-7b site received high flow water after passing through an ALD, so removal of iron was extraordinary in the succeeding AeW. The WV-7a site received water from WV-7b, and iron continued to precipitate in this system. The WV-7c AeW received water from a VFW at a low flow, but acidity declines were not apparent because the alkalinity was already quite high and not much iron was in the influent water.

Anaerobic Wetlands

The 17 anaerobic wetlands showed wide variation in acid removal (0 to 67.9 t/yr of acid load treated) and varied in treatment costs from $341/t/yr at WV-34 to $4,762 at WV-25b (Table 4). The two largest wetlands at WV-4b and WV-6 received high flows but had very different removal efficiencies. The WV-4b wetland (Fig. 2) received treated water from an ALD, which functioned well (see Table 5), but AMD from adjoining areas also flowed into the AnW thereby reducing its efficiency. The WV-6 system (Fig. 3) was very large and unique (for a more complete description, see Skousen 1995) and received the water directly from a wet seal draining an underground mine pool. The AnW effluent was alkaline for several years after its construction, but has declined in efficiency over time.

Figure 2. The WV-4b anaerobic wetland systems (AnW). This wetland system removed 3.9 $g/m^2/day$.

Figure 3. The WV-6 AnW system is a long narrow wetland along an abandoned railroad. The system was expensive to build but removes 33 $g/m^2/day$.

The smallest system (WV-16b) of 40 m^2 removed acid at a rate of 37.3 $g/m^2/day$, but the influent water had little acidity. Of the four AnWs that received alkaline water, two systems showed a further decrease in acidity, while the other two probably received acid drainage from surrounding areas. The WV-35b system had the highest removal efficiency, which was due to this system being comprised of six small alternating oxidation and reducing wetland cells. The WV-34 system (Fig. 4) was also a series of small alternating wetland cells and shows the second highest removal efficiency. These 35b and 34 systems are two of the oldest AnWs and their removal efficiency is quite remarkable over this 10-year period. All of the systems except for WV-1h (1568 m^2 and a removal rate of 2.9 $g/m^2/day$) removed acid at greater rates than the design factor of 3.5 $g/m^2/day$. It should be noted that these passive systems were designed using the highest pre-construction flow and net acidity concentrations. Our analysis was based on average flow and average acidity, rather than maximums. Therefore, our removal efficiencies will often be higher than the design factors. Five of the 17 systems did not remove acid as shown by the greater acid concentration in the effluent than the influent.

Anoxic Limestone Drains

The 36 ALDs gave a wide range of acid loads treated (between 0 to 127.3 t/yr), while costs ranged from $7 to $1,072/t/yr (Table 5). There was no apparent relationship between the pH of incoming water and the ALD's effectiveness. Using the design factor of residence time >15 hrs, mass of limestone in the ALDs varied between 8 to 6,930 t and the residence time varied between 1 and 240 hrs (Fig. 5). Most of the systems had residence times of between 20 and 100 hrs (see comment above about initial sizing and average flows). It is most interesting that the highest removal efficiencies were with ALDs with 6, 4, and 2 hrs residence times. The WV-23f ALD changed the acidity from 416 mg/L acidity to 142 mg/L alkalinity with a residence time of

6 hrs, while the WV-28a site had a residence of 4 hrs, yet changed acidity concentration from 396 to 98 mg/L, with a removal efficiency of 507 g/day/t. The site with the longest residence time of 240 hrs, WV-35a, changed the acidity from 2389 to 1277 mg/L, and the removal efficiency was quite respectable at 30 g/day/t. There were eight systems that held the water for less than 15 hrs, and two of these showed increases in acidity. We also calculated removal efficiency and found that these ALDs varied from 0 to 675 g/day/t, with an average of about 86 g/day/t. 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 tonne of acid removed. This is an amazing result, since many of these systems have been in place for 3 to 9 years. Many people assume that ALDs are a passive treatment type prone to failure. Our results show better than expected success.

Figure 4. The WV-34 site contains six cells, the first three are seen here. The first red pond collects the seepage from the hillside, then the water is routed through these anaerobic cells. This system has removed an average of 39 g/m^2/day.

Figure 5. The WV-1a ALD removed an average of 74 g/day/t of acidity, which was a high removal efficiency for ALDs.

Vertical Flow Wetlands

Fifteen of 16 VFWs reduced acidity concentrations and acid loads. They showed wide variation in treatment cost from $13 at MD-1c to $2,494/t/yr at MD-3c (Table 6). Sizes of VFWs ranged from 130 to 4,156 m^2, and removal rates varied from 0 to 843 $g/m^2/day$. Two systems removed acid at a rate of >200 $g/m^2/day$ (MD-1c and KY-1), five removed acid at a rate of between 39 to 87 $g/m^2/day$, and eight removed acid at a rate of 2 to 17 $g/m^2/day$ (Fig. 6). These removal rates are consistent with the design factor of 20 $g/m^2/day$.

Figure 6. The WV-15 VFW and Pond systems received acidic water (in the foreground) from seepage, which was routed through the WV-15c VFW, then to the WV-15a Pond. From there, the water flowed through the WV-15d VFW and then through the WV-15b Pond. The 15-c VFW removed around 7 $g/m^2/day$, the 15-d VFW removed around 2 $g/m^2/day$, while the Ponds removed only small amounts of acidity (<1 $g/m^2/day$).

Table 4. Influent and effluent characteristics, acid load treated, construction costs and efficiencies for Anaerobic Wetlands (AnW).

Site	N	Flow (L/s)	pH In	pH Out	Net Acidity In (mg/L)	Net Acidity Out (mg/L)	Acid Load Treated (t/yr)	Size (m^2)	Years in Service (yrs)	Construction Cost ($)	Service Life (yrs)	Removal Efficiency ($g/m^2/day$)	Cost Efficiency ($/t/yr)
WV-25a	11	0.3	3.0	3.0	136	163	0	558	10	100,000	20	0	0
WV-28d	21	1.5	5.8	5.8	226	267	0	130	9	47,529	20	0	0
WV-22b	13	0.4	6.5	5.5	-168	28	0	149	5	4,983	20	0	0
WV-2d	7	2.4	6.7	6.8	-200	-162	0	920	4	38,549	20	0	0
WV-28c	21	1.9	5.7	5.7	98	173	0	130	9	23,823	20	0	0
WV-34	20	1.7	2.9	2.9	1410	1040	22.0	1,412	10	150,219	20	38.8	341
WV-35b	8	0.9	2.5	2.6	1112	588	16.5	862	10	116,184	20	47.6	352
WV-30k	9	0.6	4.6	5.2	231	96	2.8	223	5	20,000	20	32.2	357
WV-6	63	10.9	3.0	4.9	259	81	67.9	5,064	7	549,901	20	33.3	405
WV-16b	7	1.2	6.0	6.2	0	-15	0.6	40	4	4,947	20	37.3	412
WV-2e	7	2.4	7.2	7.1	-162	-177	1.3	334	4	14,026	20	9.6	539
WV-4b	5	4.4	5.9	6.2	74	25	7.5	4,740	4	97,925	20	3.9	653
WV-30l	8	0.6	4.3	6.0	83	-2	1.2	297	5	20,000	20	10.0	833
WV-29	6	1.9	3.0	3.7	147	90	3.8	812	10	97,143	20	11.6	1,278
WV-1h	3	0.6	3.0	4.6	134	45	1.8	1,568	5	125,187	20	2.9	3,477
WV-25b	11	0.4	2.9	3.4	357	239	1.6	1,185	10	152,375	20	3.6	4,762

Table 5. Influent and effluent characteristics, acid load treated, construction costs and efficiencies for Anoxic Limestone Drains (ALD).

Site	N	Flow (L/s)	pH In	pH Out	Net Acidity In (mg/L)	Net Acidity Out (mg/L)	Acid Load Treated (t/yr)	Size (t)	Years in Service (yrs)	Construction Cost ($)	Service Life (yrs)	Residence Time (>15 hrs)	Removal Efficiency (g/day/t)	Cost Efficiency ($/t/yr)
WV-23a	10	10.2	3.8	3.0	104	308	0	8	8	12,298	20	1	0	0
WV-23b	10	0.8	3.1	3.0	420	444	0	15	9	18,876	20	2	0	0
WV-30f	7	0.3	6.1	6.3	9	196	0	140	5	3,779	20	37	0	0
WV-28b	5	1.5	3.1	5.8	591	226	19.1	250	9	2,656	20	13	190.0	7
WV-4a	4	3.0	2.9	5.9	405	74	34.8	409	4	11,041	20	11	211.7	16
OH-1c	8	1.7	2.9	4.7	712	157	33.0	720	2	18,154	20	34	114.0	27
WV-32	6	0.4	2.9	4.9	1064	340	10.1	215	4	5,747	20	43	116.7	28
WV-7d	5	0.6	5.8	6.6	18	-173	4.0	88	3	2,377	20	12	113.1	30
WV-30b	5	0.6	6.3	6.6	50	-214	5.5	123	5	3,321	20	16	111.2	30
WV-26	5	0.1	3.0	6.6	1515	-41	5.4	128	8	3,488	20	102	104.9	32
WV-1a	3	12.9	3.7	6.8	96	-186	127.3	4,267	5	115,207	20	26	74.2	45
WV-30g	7	0.3	2.9	6.3	631	14	6.4	315	5	8,505	20	84	50.5	66
WV-22a	6	0.4	2.7	6.5	730	-168	12.5	652	5	17,299	20	130	47.7	69
WV-1b	3	11.9	3.7	6.6	96	-195	121.1	6,222	5	167,994	20	42	53.5	69
WV-23f	10	0.2	3.6	6.6	416	-142	3.8	14	8	5,365	20	6	675.2	70
WV-2c	4	2.3	4.1	6.3	307	-53	28.9	1,583	4	42,743	20	55	45.4	74
WV-19a	4	0.4	3.3	6.9	1020	-210	17.2	972	3	26,301	20	194	44.0	76
WV-1d	3	1.9	3.7	6.1	96	-37	8.8	517	5	13,957	20	22	46.6	79
WV-28a	10	1.9	3.0	5.7	396	98	19.8	97	9	6,829	20	4	507.8	86
WV-30e	6	0.3	4.3	5.8	88	-38	1.3	90	5	2,430	20	24	35.9	93
WV-35a	8	0.2	2.9	5.9	2389	1277	7.8	600	1	15,903	20	240	29.9	102
WV-19b	4	0.3	3.3	5.5	1020	188	8.7	702	3	19,050	20	187	30.8	109
WV-23h	10	2.3	3.4	5.1	434	337	7.8	51	9	17,446	20	2	380.5	112

Table 5 Continued

MD-3a	7	1.0	4.0	6.4	299	73	7.9	770	5	20,790	20	62	25.5	132
WV-5	2	3.8	3.8	5.8	79	10	9.2	955	2	25,783	20	20	24.7	139
WV-16a	7	1.0	3.3	6.2	201	-107	10.7	1,194	4	32,238	20	96	22.3	151
WV-30a	7	0.2	5.2	6.7	139	-93	1.6	276	5	7,452	20	110	14.4	233
WV-23d	10	0.1	3.9	4.1	874	641	0.8	66	9	4,004	20	53	30.2	250
WV-7e	5	3.7	4.1	6.3	66	-157	28.8	6,285	3	169,695	20	136	11.4	295
WV-23c	10	0.1	3.8	3.8	963	874	0.3	43	9	2,574	20	34	17.4	429
WV-8a	20	1.5	3.5	5.5	668	594	3.9	1,265	5	34,208	20	67	7.7	438
WV-30d	5	0.1	6.3	6.3	216	117	0.3	110	5	2,969	20	88	7.5	495
WV-17	19	2.6	3.1	7.0	131	-59	17.2	6,930	12	187,110	20	213	6.2	544
WV-8b	29	0.8	3.4	5.9	718	648	1.9	940	5	25,099	20	94	5.0	661
WV-1c	3	0.6	3.7	6.3	98	-25	2.5	1,480	5	39,961	20	197	4.6	799
WV-23e	10	0.1	3.4	3.7	531	465	0.2	118	9	4,290	20	94	4.2	1,072

Table 6. Influent and effluent characteristics, acid load treated, construction costs and efficiencies for Vertical Flow Wetlands (VFW).

Site	N	Flow (L/s)	pH In	pH Out	Net Acidity In (mg/L)	Net Acidity Out (mg/L)	Acid Load Treated (t/yr)	Size (m^2)	Years in Service (yrs)	Construction Cost ($)	Service Life (yrs)	Removal Efficiency ($g/m^2/day$)	Cost Efficiency ($/t/yr)
OH-2d	6	0.9	6.8	6.8	13	14	0.0	150	1	14,486	20	0	0
MD-1c	7	1.7	2.8	6.7	841	-215	62.7	185	3	16,880	20	843.1	13
KY-1	16	2.3	2.8	5.1	843	22	66.1	800	1	74,046	20	205.5	56
WV-3a	6	0.7	3.0	6.3	141	-125	6.5	185	3	14,313	20	87.4	110
OH-1b	8	2.0	3.4	6.9	176	-99	19.2	590	2	58,945	20	80.9	153
MD-1a	7	0.4	6.1	7.2	365	83	3.9	130	3	12,771	20	74.6	164
WV-3b	6	0.3	2.9	6.0	195	-117	3.2	204	3	15,753	20	39.0	246
WV-15c	2	0.4	2.7	6.3	499	185	4.3	1,493	3	56,878	20	7.2	661
MD-2b	3	1.0	6.7	7.1	-20	-109	3.1	650	3	43,878	20	11.9	708
OH-2a	6	0.9	3.6	6.0	127	81	1.4	200	1	19,898	20	17.4	711
WV-7f	5	0.6	5.8	6.6	18	-237	5.3	1,484	3	89,314	20	8.9	842
WV-16e	7	1.2	6.2	6.4	-20	-32	0.5	148	4	11,208	20	8.4	1,121
WV-3c	5	0.1	3.0	5.1	134	0	0.4	148	3	11,461	20	6.7	1,433
WV-15d	2	0.4	4.9	6.9	134	-89	3.1	4,156	3	125,406	20	1.9	2,023
WV-1g	3	1.2	3.4	6.8	53	-62	4.8	3,061	5	213,267	20	3.9	2,221
MD-3c	7	1.0	6.7	6.7	24	6	0.8	584	3	39,907	20	3.4	2,494

The WV-3a site has been very successful in removing acidity. Recently it has shown some decline in treatment efficiency due to a large building up of iron hydroxide floc on the surface. These systems are prone to having problems with the organic material due to this thick floc, which can reduce the flow of water resulting in break through or channeling of water to the limestone (Demchak et al. 2001) or complete plugging of the organic material. Increasing the drainage through the system by more drainage lines or layers of pipes in the limestone has been designed lately (Denholm et al., 2004). This effort is supposed to allow removal of the flocs collecting in the limestone by flushing them from the limestone pores. Watzlaf et al. (2002) showed that flushing of VFWs in Pennsylvania removed less than 1% of the iron that was calculated to have been retained in the VFW. The velocity and movement of water through limestone for floc removal would have to be very great and it does not appear to be enough to remove flocs. Anecdotal comments from ALD and VFW builders reflect that much greater shaking or sucking actions (such as that of small explosives being detonated in the system or suction trucks being attached to the effluent pipes) are needed to move flocs from limestone pore spaces.

Open Limestone Channels

Ten OLCs were evaluated in this study, and all but one reduced the acidity concentrations in the water and showed some acid load reduction (Table 7). The cost of treatment varied between 26 and $7,523/t/yr. Except for the last two (WV-33c and 12a), all of these OLCs treated water at or less than $300/t/yr. Residence times were not calculated because we could not determine the length of time the water flowed in the channels (we did not know the water velocities and slopes). However, we calculated removal efficiencies and found most of them to remove about 15 to 20 g/day/t. The average removal was 30.2 g/day/t. The WV-14 site was a channel on a 15% slope (Fig. 8). It received the water from a small underground mine, but also received surface runoff during rain events. These rain events introduced sediments to the channel which scoured the limestone periodically. The WV-36a (Fig. 7) and 36b channels are unique in that they receive large flows of low pH water with few to no metals. The 36a site has an exceptionally high removal efficiency of 121 g/day/t, and this is undoubtedly due to the fact that the limestone is not armored with iron. The high removal rate is based on neutralizing primarily hydrogen ion acidity and dissolution continues without the problem of armoring. This system is operating much more like the design for a LSB.

Table 7. Influent and effluent characteristics, acid load treated, construction costs and cost efficiencies for Open Limestone Channels (OLC).

Site	N	Flow (L/s)	pH In	pH Out	Net Acidity In (mg/L)	Net Acidity Out (mg/L)	Acid Load Treated (t/yr)	Size (t)	Years in Service (yrs)	Construction Cost ($)	Service Life (yrs)	Removal Efficiency (g/day/t)	Cost Efficiency ($/t/yr)
WV-12a	6	8.0	3.5	3.4	66	87	0	2,350	2	34,992	20	0	0
WV-36a	35	41.7	5.5	5.7	20	10	14.6	300	1	7,500	20	121.1	26
WV-14	3	10.9	3.7	3.9	212	141	27.1	889	6	24,004	20	75.8	44
WV-31	6	1.3	2.9	4.5	692	55	28.9	2,711	4	73,184	20	26.5	127
WV-12c	6	12.2	4.2	5.5	76	56	8.6	892	2	28,099	20	26.4	163
WV-24	3	11.9	4.0	5.5	41	7	14.1	1,785	2	46,272	20	19.6	164
WV-11	2	1.8	2.5	2.6	849	727	7.6	1,248	3	36,192	20	15.1	238
WV-36b	35	9.9	5.6	6.0	8	2	2.1	450	1	11,250	20	11.6	268
WV-12b	6	2.1	3.5	5.3	66	30	2.6	1,170	2	31,590	20	5.5	607
WV-33c	6	0.3	5.1	5.5	28	12	0.1	600	5	15,046	20	0.4	7,523

Figure 7. The WV-36a OLC had the highest removal efficiency of all the OLCs we sampled at 121 g/day/t. The influent water had a pH of about 5.5 with no metals.

Figure 8. The WV-14 OLC is armored by iron hydroxides, but still has removed an average of 76 g/day/t of acidity. The channel is on a slope of about 15% and receives the drainage from an underground portal. It also receives the runoff from the surrounding hillside, which provides an opportunity for the iron coatings to be flushed during high flow events.

Limestone Leach Beds

Limestone beds have been extensively installed in Alabama and Tennessee, with a few in WV (Fig. 9). All 17 systems gave acidity reductions (Table 8). These systems removed between 1 and 60 t/yr of acid load. Using the same technique for calculating residence time as ALDs, the masses in these LSBs ranged from 414 to 6,250 t and the residence time of these systems varied between 8 and 833 hrs, with most being between 10 and 70 hrs. All of them had a residence time of >1.5 hrs of residence time as suggested. Removal efficiencies were between 0.4 and 40 g/day/t with an average of 17.6 g/day/t. These, along with ALDs, were among the most efficient systems in this study. Theoretically, these systems should maintain their removal efficiency until the limestone is exhausted or the limestone surface area decreases due to burial or some armoring.

Figure 9. The WV-36d LSB receives low pH water with no metals. Under this condition, the limestone is not armored and continues to dissolve. The removal efficiencies have remained constant from 10 g/day/t in 1999-2000 to 14 g/day/t in 2004.

Slag Leach Beds

Slag leach beds are a new technology and only two were available for evaluation (Table 9). They were in place for only 1 or 2 years at the time of monitoring. One bed had extremely high removal efficiency at >4,000 g/day/t, while the other had a very removal efficiency at 237 g/day/t. Steel slag has the potential of generating much higher levels of alkalinity than limestone and as such should provide much greater treatment potential. However, the small sample size and their newness, due to their recent construction and short service life, make us cautious in interpreting the results. Nonetheless, both projects reduced the acidity concentrations and the acid load very cheaply.

Table 8. Influent and effluent characteristics, acid load treated, construction costs and efficiencies for Limestone Leach Beds (LSB).

Site	N	Flow (L/s)	pH In	pH Out	Net Acidity In (mg/L)	Net Acidity Out (mg/L)	Acid Load Treated (t/yr)	Size (t)	Years in Service (yrs)	Construction Cost ($)	Service Life (yrs)	Residence Time (>15 hrs)	Removal Efficiency (g/day/t)	Cost Efficiency ($/t/yr)
TN-1d	7	19.1	3.0	5.4	118	28	60.1	3,737	2	93,436	20	16	40.0	78
AL-2b	2	7.3	7.0	6.8	-29	-72	10.9	730	4	17,527	20	8	37.1	80
WV-13a	3	0.4	3.1	6.0	432	-100	7.4	523	5	14,122	20	105	35.2	95
WV-13b	3	0.9	2.8	3.1	646	432	6.7	523	5	14,122	20	46	31.9	105
IN-2a	48	4.7	2.7	4.8	515	230	46.9	4,000	2	100,000	20	68	29.2	107
TN-1c	7	22.1	2.9	4.0	93	48	34.8	2,996	6	74,911	20	11	28.9	108
TN-1b	7	16.4	3.1	5.0	71	17	31.0	3,960	3	98,989	20	19	19.5	160
TN-2c	5	2.3	2.3	3.4	701	293	32.9	4,800	4	120,000	20	167	17.1	182
TN-2b	5	6.3	2.5	3.3	286	177	24.1	4,740	6	113,783	20	60	13.9	236
AL-1	4	1.6	3.8	7.5	92	-42	7.4	1,490	1	35,825	20	74	13.6	242
WV-9	3	0.2	3.3	7.0	262	-46	2.1	414	4	10,350	20	166	12.6	246
WV-36d	35	11.8	5.6	4.4	8	-7	6.1	1,500	1	37,500	20	10	10.1	307
AL-2c	2	5.1	3.9	7.6	26	-33	10.5	4,210	4	100,997	20	66	6.2	481
AL-2a	2	2.8	6.7	7.6	-28	-56	2.7	1,560	4	37,667	20	44	4.3	697
TN-2d	5	0.9	2.6	3.5	359	103	8.1	4,530	3	113,437	20	403	4.5	700
TN-1a	7	1.6	3.2	6.2	70	-44	6.3	4,375	4	104,991	20	219	3.6	833
TN-2a	5	0.6	2.9	4.1	245	188	1.2	6,250	8	150,530	20	833	0.5	6,272

Table 9. Influent and effluent characteristics, acid load treated, construction costs and efficiencies for slag leach beds (SLB).

Site	N	Flow (L/s)	pH In	pH Out	Net Acidity In (mg/L)	Net Acidity Out (mg/L)	Acid Load Treated (tonnes/yr)	Size (tons)	Years in Service (years)	Construction Cost ($)	Service Life (years)	Removal Efficiency (g/day/t)	Cost Efficiency ($/tonne/yr)
OH-1a	9	37.8	3.7	4.3	173	72	133.6	75	2	77,239	20	4,431	28
WV-37	24	6.6	4.4	6.4	46	-37	19.1	200	1	31,970	20	237	84

Summary of 2000 Results:

This project evaluated AMD treatment by 116 passive system units ranging in age from 1 to 12 years. Reductions in acidity concentrations and acid load were measured at 105 of the 116 sites (90%). Table 10 summarizes the performance of the various treatment technologies by providing averages for acid load treated, construction costs, removal rates, and cost efficiency. Given that the number of treatment units per technology ranged from 2 to 37, the performance average values are not directly comparable, but provide an indication of the treatment results possible and provide a probable range of treatment efficiencies and costs with these passive treatment system types. Average amounts of acid treated ranged from 0.7 t/yr for Ponds to 76 t/yr for SLBs.

Table 10. Summary of the treatment effectiveness of passive treatment systems.

System Type	Number of Units	Average Acid Treated (t/yr)	Average Total Cost ($)	Average Removal (g/day/t, g/m^2/day)	Average Cost ($/t/yr)	% of Systems That Removed Acid
AeW	6	9.1	10,565	16.3 g/m^2/day	59	100
ALD	37	15.4	29,726	86.1 g/day/t	96	92
OLC	10	10.6	30,813	30.2 g/day/t	145	90
SLB	2	76.3	54,604	2,334 g/day/t	36	100
LSB	17	17.6	72,835	18.1 g/day/t	207	100
VFW	16	11.6	51,151	87.5 g/m^2/day	220	94
AnW	17	8.0	94,515	16.4 g/m^2/day	591	71
Ponds	11	0.8	10,035	1.7 g/m^2/day	1,468	82
Total:	116					

The average cost efficiency ($/t/yr) of acid removed ranged from $36 for SLBs to $1,468 for Ponds (Table 10). It is interesting to note that ALDs and OLCs were similar in average cost, while LSBs and VFWs were relatively close at around $200/t/yr. Anaerobic wetlands had the highest average construction cost, but this average cost was high because of one exceptionally expensive unit (the WV-6 site, Skousen 1995). Removing this one system from the list would have reduced the average construction cost from $94,000 to $66,000, much closer to the construction costs for SLBs, LSBs, and VFWs, and the average cost would have been around $400/t/yr instead of $600/t/yr. We also found that removal rates were, for the most part, as good as or better than the amounts established as design factors by other researchers, but this is due to the use of maximum measured flows and net acidities for design and sizing, rather than average values that we used for determining removal efficiencies. Anaerobic wetlands removed acidity at a rate of 2.5 to 50 g/m^2/day with an average of 17.5, compared to the design factor of 3.5. VFWs removed acidity at an average of about 60 g/m^2/day, and this can be compared to a design factor of 50 g/m^2/day. Residence times of >15 hrs also appear to be adequate for acidity reductions in ALDs and LSBs. Removal efficiencies for ALDs, OLCs, and LSBs varied between 18 to 80 g/day/t.

2004 Study

Much of the data presented above were developed from a large study of passive systems that had been sampled as early as 1988. The last sampling of most of these systems was done in 2000. We selected a few of these systems and re-sampled them in 2004 to see if the results that we found for each of the system types could be confirmed in 2004 or if treatment had changed during the past four years. Table 11 shows the pond and wetland systems we selected and the data associated with the previous sampling (1997-2000) and with our sampling (2004). The two Ponds had slightly higher removal efficiencies in 2004 as those found earlier. The influent water had nearly doubled in acidity and as a result, the removal efficiency was about 30% higher. This is an interesting result since higher flows reduced residence time and should have decreased removal efficiency. It is not clear but it is possible that we are seeing more iron precipitation in these Ponds with time. The WV-6 anaerobic wetland decreased in removal efficiency between the two sampling dates and the flow was slightly higher and the acid concentration was slightly lower. The total amount of acid load removed by this system decreased from 68 to 24 tons per year. This system may be showing the effects of age after 10 years of floc collection, and hence limestone dissolution has slowed along with a decrease in organic matter adsorption capacity. The three VFWs at the WV-3 site showed every possible change. The WV-3a system showed a decline in flow but gave similar acid concentrations in the effluent water. So while the t/yr of acid decreased, with concurrent decreases in removal efficiency and cost efficiency, the VFW seems to be doing about the same treatment action. The 3b system has improved the alkalinity output of the water, which translates into an increased removal efficiency and a lower cost. The water going into and out of the 3c system has changed dramatically, but the same amount of alkalinity seems to be produced, which reflects a similar removal efficiency. A similar divergence in treatment effectiveness is apparent in the WV-15 VFWs.

Variations were also found for the limestone-based systems (Table 12). The WV-17 ALD showed slightly lower removal efficiency, but lower efficiency is probably related to the lower flow in 2004 compared to 1988-2000 data. Lower flow translated into more residence time and the acid concentration in the effluent water was further reduced (-59 vs -115 mg/L). The two OLCs at WV-36 both show greater removal efficiencies, but again the flows of water through these systems have increased substantially but have not changed the acid concentrations in the effluent much between years. For the other two OLCs, WV-11 did not change, while WV-14 declined in efficiency but increased greatly in flow. Continued monitoring of some of the other systems in this study will give us greater insight as to the longevity of treatment for these systems.

Table 11. Influent and effluent characteristics, acid load treated, construction costs and efficiencies for passive systems. Efficiencies are based on m^2 area (P, AnW, and VFW).

System Type	Site (Time)	N	Flow (L/s)	pH In	pH Out	Net Acidity In (mg/L)	Net Acidity Out (mg/L)	Acid Load Treated (t/yr)	Size (m^2)	Years in Service (yrs)	Construction Cost ($)	Service Life (yrs)	Removal Efficiency ($g/m^2/day$)	Cost Efficiency ($/t/yr)
Ponds	WV-15a (97-00)	2	0.4	2.7	2.7	528	499	0.4	1,563	3	14,934	20	0.6	1,867
	WV-15a (2004)	2	0.4	2.6	3.0	848	799	0.7	1,563	7	14,934	20	1.1	1,067
	WV-15b (97-00)	2	0.4	4.3	4.9	185	134	0.7	2,151	3	25,719	20	0.8	1,837
	WV-15b (2004)	2	0.4	3.3	3.2	364	280	1.1	2,151	7	25,719	20	1.3	1,169
AnW	WV-6 (94-00)	60	10.9	3.0	4.9	259	81	67.9	5,064	7	549,901	20	33.3	405
	WV-6 (2003)	3	11.2	2.9	3.3	188	127	23.9	5,064	10	549,901	20	11.7	1,150
VFW	WV-3a (97-00)	6	0.7	3.0	6.3	141	-125	6.5	185	3	14,313	20	87.4	110
	WV-3a (2004)	2	0.2	3.1	7.6	104	-120	1.6	185	7	14,313	20	21.0	457
	WV-3b (97-00)	6	0.3	2.9	6.0	195	-117	3.2	204	3	15,753	20	39.0	246
	WV-3b (2004)	2	0.3	3.1	7.7	150	-320	4.8	204	7	15,753	20	58.5	164
	WV-3c (97-00)	6	0.1	3.0	5.1	134	0	0.4	148	3	11,461	20	6.7	1,433
	WV-3c (2004)	2	0.1	3.2	7.9	10	-120	0.4	148	7	11,461	20	6.7	1,433
	WV-15c (97-00)	2	0.4	2.7	6.3	499	185	4.3	2,497	3	56,878	20	4.2	661
	WV-15c (2004)	2	0.4	3.0	3.3	799	364	6.1	2,497	7	56,878	20	6.1	466
	WV-15d (97-00)	2	0.4	4.9	6.9	134	-89	3.0	4,156	3	125,406	20	1.8	2,090
	WV-15d (2004)	2	0.4	3.2	3.5	280	145	1.9	4,156	7	125,406	20	1.1	3,300

Table 12. Influent and effluent characteristics, acid load treated, construction costs and efficiencies for limestone passive systems, and efficiencies are based on mass of limestone (ALD, OLC, LSB).

System Type	Site (Time)	N	Flow (L/s)	pH In	pH Out	Net Acidity In (mg/L)	Net Acidity Out (mg/L)	Acid Load Treated (t/yr)	Size (t)	Years in Service (yrs)	Construction Cost ($)	Est. Service Life (yrs)	Residence Time (>15 hrs)	Removal Efficiency (g/day/t)	Cost Efficiency ($/t/yr)
ALD	WV-17 (88-00)	19	2.6	3.1	7.0	131	-59	17.2	6,930	12	187,110	20	213	6.2	544
	WV-17 (2004)	3	1.4	3.2	7.0	139	-115	12.4	6,930	15	187,110	20	296	4.5	754
OLC	WV-11 (97-00)	2	1.8	2.5	2.6	849	727	7.6	1,248	3	36,192	20		15.1	238
	WV-11 (2004)	2	1.5	2.6	2.8	1022	881	7.4	1,248	7	36,192	20		14.8	244
	WV-36a (01-02)	35	41.7	5.5	5.7	20	10	14.6	300	1	7,500	20		121.1	26
	WV-36a (2004)	8	189	4.6	4.7	16	9	46.3	300	3	7,500	20		383.1	8
	WV-36b (01-02)	35	9.9	5.6	6.0	8	2	2.1	450	1	11,250	20		11.6	268
	WV-36b (2004)	8	138	4.6	4.7	16	13	14.5	450	3	11,250	20		80.1	39
	WV-14 (94-00)	3	10.9	3.7	3.9	212	141	27.0	889	6	24,004	20		75.5	44
	WV-14 (2004)	8	12.6	3.2	3.4	180	145	15.4	889	9	24,004	20		43.1	78
LSB	WV-36d (01-02)	3	11.8	4.4	5.7	8	-7	6.2	1,500	1	37,500	20		10.3	302
	WV-36d (2004)	8	138	4.6	4.7	16	13	14.5	1,500	3	37,500	20		13.9	223

Discussion and Summary

Acid removal by Ponds and AeWs can occur at low pH as water is collected from seepage or underground mines and is allowed to oxidize. Acidity concentrations can decrease in water as CO_2 is exsolved. As ferrous iron is oxidized, the resulting ferric iron will precipitate in these structures as long as the pH is around 3.0 through hydrolysis and precipitation. These structures also provided the anticipated result of iron, aluminum and other co-precipitated metals settling out of the stagnant water.

The AnWs in this study were quite consistent and had a narrow range of removal efficiencies of all the system types. They remain, in our opinion, fairly robust systems that work well if not overwhelmed with acid or metal loads. We noticed AnWs that were filled with metal oxyhydroxides, which has caused the wetlands to decline in treatment efficiency. These wetlands need to be renovated by removing the floc and exhausted substrate and replacing it with fresh limestone and organic matter. The materials removed are a mixture of limestone, organic material and iron and aluminum hydroxides, which can be an excellent topsoiling material when spread on the surface and allowed to dry. A maintenance schedule for cleaning the AnWs and replacing the substrate is probably a very much needed strategy that needs to be put in place for these systems treating high metal loads.

The ALDs were a surprise to us. Most of them were effective and efficient, and only a few showed no treatment. It is clear that some of these systems were not performing optimally as shown by the effluent pH being less than 6.0. The design factor of 15 hrs of contact time between limestone and water has been noted, however, not much work has been done on systems that have rapid flow through, shorter residence times, and hence less time for floc buildup or precipitation in the limestone. It is apparent from our data that high removal efficiencies were found with ALDs with as little as 2 hrs of residence time. With this in mind, ALDs could possibly be designed so that water is in contact with the limestone for only a short time. The alkalinity generated by limestone dissolution may only raise the pH to 3.5 or 4.0, but be sufficient to precipitate iron and aluminum outside of the drain. This may be a way to decrease the likelihood of failure due to metal hydroxide plugging. In fact, an optimum design may result in the placement of a narrow long channel of limestone on a slope where the water is flowing underground through the limestone trench, much like an underground OLC.

The VFWs appear to be working well with removal efficiencies well above the design standards. The latest designs for these systems are getting quite complicated with multiple drainage pipes at different levels in the limestone (Denholm et al. 2004). While the hypothesis that the metal hydroxide flocs are removed from the limestone through these drainage systems, the evidence suggests that it is not removed. If anything, the only metal flocs removed from the system are those within the pipes, not the limestone (Watzlaf et al. 2002). In many respects, these VFWs are acting like very deep AnWs, where the substrates will need to be removed as the metal flocs build up and fill the structure. The drainage system will only be a hindrance to the cleanout of these systems.

The OLCs work best where little to no iron is in the water to coat the limestone. Such an OLC at WV-36a showed high acid removal rates undoubtedly due to dissolution of unarmored limestone. Scouring of coatings from the limestone surface by periodic flushing with sediment-laden runoff is a good strategy for cleaning the surface of limestone particles and producing fresh surface area. The limestone and slag leach beds work best in metal free, low pH water allowing for dissolution of limestone and maximum generation of alkalinity.

Limestone is a key component in passive treatment systems. Iron is the key element of concern, which causes systems to fail due to armoring or floc buildup. Passive systems with low iron or that have had the iron removed before introduction into a passive system have a much greater chance of remaining viable and effective.

Passive system designers and reclamation planners need to know which system types provide the greatest return per dollar and general removal efficiencies. This analysis is a first attempt at evaluating passive system performance across a variety of system types and across a wide range of water flows and qualities. Strategies for maintaining these systems are needed to make the systems efficient for acid removal. Costs for these maintaining these systems need to be developed.

Acknowledgments

Special thanks are given to the WV Dept. of Environmental Protection, Div. of Abandoned Mine Land and Reclamation (Charlie Stover, Pat Park, Pete Pitzenbarger, and Charlie Miller). We also especially thank Ben Faulkner, Lindsay Abraham, Eric Danaway, Mike Sheehan, Sheila Vukovich, and Marshall Leo.

References

Black, C., P. Ziemkiewicz, and J. Skousen. 1999. Construction of a limestone leach bed and preliminary water quality results in Beaver Creek. In: Proceedings, Twentieth West Virginia Surface Mine Drainage Task Force Symposium, Morgantown, WV.

Bolis, J.L., T.R. Wildeman, and R.R. Cohen. 1991. The use of bench-scale parameters for preliminary analysis of metal removal from acid mine drainage by wetlands. p. 123-126. In: Wetlands Design for Mining Operations. Proc. Conf. of Amer. Soc. for Surface Mining and Reclamation, May 14-17, Durango, CO.

Brodie, G.A. 1993. Staged, aerobic constructed wetlands to treat acid drainage: Case history of Fabius Impoundment 1 and overview of the Tennessee Valley Authority Program. p. 157-166. In: G.A. Moshiri (ed.), Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Boca Raton, FL. 632 pp.

Brodie, G.A., C.R. Britt, H. Taylor, T. Tomaszewski, and D. Turner. 1990. Passive anoxic limestone drains to increase effectiveness of wetlands acid drainage treatment systems. In: Proceedings, Twelfth National Association of Abandoned Mined Land Conference, Breckinridge, CO.

Brooks, R., D.E. Samuel, and J.B. Hill. 1985. Wetlands and water management on mined lands. Proceedings of a Conference. The Pennsylvania State University, University Park, PA. 393 pp.

Calabrese, J.P., A.J. Sexstone, D.K. Bhumbla, G.K. Bissonnette, and J.C. Sencindiver. 1991. Application of constructed cattail wetlands for the removal of iron from acid mine drainage, p. 559-575. In: Proceedings, Second International Conference on the Abatement of Acidic Drainage, September 16-18, 1991, Vol. 3, MEND, Montreal, Canada.

Demchak, J., T. Morrow, and J. Skousen. 2001. Treatment of acid mine drainage by vertical flow wetlands in Pennsylvania. Geochemistry, Exploration, Environment, Analysis 2:71-80.

Denholm, C., P. Shah, T. Hilton, T. Danehy, S. Busler, and M. Dunn. 2004. Operation and maintenance considerations for a passive system treatment complex. p. 241-248. In: Proceedings, 2004 American Society for Mining and Reclamation and 26th Surface Mine Drainage Task Force Symposium, April 19-23, 2004, Morgantown, WV.

Duggan, L.A., T.R. Wildeman, and D.M. Updegraff. 1992. The aerobic removal of manganese from mine drainage by an algal mixture containing Cladophora. In: Proceedings, Ninth American Society for Surface Mining and Reclamation Conference, June 14-18, 1992, Duluth, MN.

Eger, P. 1992. The use of sulfate reduction to remove metals from acid mine drainage. p. 563-575. In: Proceedings, Ninth Amer. Soc. for Surface Mining and Reclamation Conference, June 14-18, 1992, Duluth, MN.

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.

Faulkner, B.B., and J.G. Skousen. 1994. Treatment of acid mine drainage by passive treatment systems. p. 250-257. In: Proceedings, International Land Reclamation and Mine Drainage Conference, April 24-29, 1994, USDI, Bureau of Mines SP 06A-94, Pittsburgh, PA.

Faulkner, B.B., and J.G. Skousen. 1995. Effects of land reclamation and passive treatment systems on improving water quality. Green Lands 25(4): 34-40.

Gusek, J. 1998. Three case histories of passive treatment of metal mine drainage. In: Proceedings, Nineteenth West Virginia Surface Mine Drainage Task Force Symposium, April 7-8, 1998, Morgantown, WV.

Gusek, J., and T. Wildeman. 2002. Passive treatment of aluminum-bearing acid rock drainage. In: Proceedings, Twenty-Third West Virginia Surface Mine Drainage Task Force Symposium, April 16-17, 2002, Morgantown, WV.

Hedin, R.S., and R.W. Nairn. 1990. Sizing and performance of constructed wetlands: case studies. p. 385-392. In: Proceedings, 1990 Mining and Reclamation Conference, April 23-26, 1990, West Virginia University, Morgantown, WV.

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

Hedin, R.S., G.R. Watzlaf, and R.W. Nairn. 1994b. Passive treatment of acid mine drainage with limestone. J. Environ. Qual. 23:1338-1345.

Hellier, W.W. 1996. The Bark Camp Run constructed wetlands: findings and recommendations for future design criteria. p. 550-559. In: Proceedings, Thirteenth American Society for Surface Mining and Reclamation Conference, May 18-23, 1996. Knoxville, TN.

Hellier, W.W. 1997. Unpublished case study for ADTI project. PA DEP, Hawk Run, PA.

Hellier, W.W, E.F. Giovannitti, and P.T. Slack. 1994. Best professional judgment analysis for constructed wetlands as a best available technology for the treatment of post-mining groundwater seeps. p. 60-69. In: Proceedings, International Land Reclamation and Mine Drainage Conference, U.S. Bureau of Mines SP 06A-94, April 24-29, 1994, Pittsburgh, PA.

Henrot, J., and R.K. Wieder. 1990. Processes of iron and manganese retention in laboratory peat microcosms subjected to acid mine drainage. J. Environ. Qual. 19:312-320.

Hilton, T. 2005. Low pH – iron oxidation. In: Proceedings, Twenty-Sixth West Virginia Surface Mine Drainage Task Force Symposium, April 19-20, 2005, Morgantown, WV. http://www.wvu.edu/~agexten/landrec/05ppridx.htm

Huntsman, B.E., J.B. Solch, and M.D. Porter. 1978. Utilization of a Sphagnum species dominated bog for coal acid mine drainage abatement. Abstracts, 91st Annual Meeting Geologic Society America, Ottawa, Ontario, Canada.

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

Jage, C., C. Zipper, and R. Noble. 2001. Factors affecting alkalinity generation by successive alkalinity-producing systems: regression analysis. J. Environ. Qual. 30:1015-1022.

Karathanasis, A.D., and C.D. Barton. 1997. Unpublished case study for ADTI project. University of Kentucky, Lexington, KY.

Kepler, D.A., and E.C. McCleary. 1994. Successive alkalinity-producing systems (VFW) 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.

Kleinmann, R.L.P. 1991. Biological treatment of mine water--an overview. p. 27-42. In: Proceedings, Second International Conference on the Abatement of Acidic Drainage, September 16-18, 1991, MEND, Montreal, Canada.

McIntyre, P.E., and H.M. Edenborn. 1990. The use of bacterial sulfate reduction in the treatment of drainage from coal mines. p. 409-415. In: Proceedings, 1990 Mining and Reclamation Conference, April 23-26, 1990, West Virginia University, Morgantown, WV.

Nairn, R.W., and M.N. Mercer. 2000. Alkalinity generation and metals retention in a successive alkalinity producing system. Mine Water and the Environment 19:124-133.

Nordstrom, D. 1982. Aqueous pyrite oxidation and the consequent formation of secondary iron minerals. p. 37-62. In: J.A. Kittrick et al. (ed.), Acid Sulfate Weathering. SSSA Spec. Publ. 10. Soil Science Society of America, Madison, WI.

Pearson, F.H., and A.J. McDonnell. 1975. Use of crushed limestone to neutralize acid wastes. No. EE1, Proc. Paper 11131. J. Environ. Eng. Div., Am. Soc. Civil Eng. 101:139-158.

Rose, A., G. Alcorn, L. Phelps, and P. Bower. 2001. Case study of Pot Ridge passive treatment systems, Cambria County, Pennsylvania. p. 592-603. In: Proceedings, Eighteenth American Society for Surface Mining and Reclamation Conference, June 3-7, 2001, Albuquerque, NM.

Rose, A., and J. Dietz. 2002. Case studies of passive treatment systems: vertical flow systems. p. 776-797. In: Proceedings, Nineteenth American Society for Surface Mining and Reclamation Conference, June 9-13, 2002, Lexington, KY.

Samuel, D.E., J.C. Sencindiver, and H.W. Rauch. 1988. Water and soil parameters affecting growth of cattails. p. 367-374. In: Proceedings, Mine Drainage and Surface Mine Reclamation, April 19-21, 1988, Vol. 1, Info. Circular No. 9183, USDI, Bureau of Mines, Pittsburgh, PA.

Schmidt, T., and M. Stearns. 2001. Evaluating successes in passive treatment at Sequatchie Valley Coal Corporation in east central Tennessee. p. 604-610. In: Proceedings, Eighteenth American Society for Surface Mining and Reclamation Conference, June 3-7, 2001, Albuquerque, NM.

Sencindiver, J.C., and D.K. Bhumbla. 1988. Effects of cattails (Typha) on metal removal from mine drainage. p. 359-366. In: Proceedings, Mine Drainage and Surface Mine Reclamation, April 19-21, 1988, Vol. 1, Info. Circular No. 9183, USDI, Bureau of Mines, Pittsburgh, PA.

Skousen, J.G. 1995. Douglas abandoned mine land project: description of an innovative acid mine drainage treatment system. Green Lands 25(1):29-38.

Skousen, J., A. Rose, G. Geidel, J. Foreman, R. Evans, and W. Hellier. 1998. A handbook of technologies for avoidance and remediation of acid mine drainage. Acid Drainage Technology Initiative (ADTI), National Mine Land Reclamation Center, West Virginia University, Morgantown, WV. 131 pp.

Skousen, J., A. Sexstone, and P. Ziemkiewicz. 2000. Acid mine drainage control and treatment. p. 131-168. In: R. Barnhisel et al. (eds.), Reclamation of Drastically Disturbed Lands. Agronomy Monograph 41, American Society of Agronomy, Madison, WI.

Skousen, J., and P. Ziemkiewicz. 1996. Acid mine drainage control and treatment. Second Edition. National Mine Land Reclamation Center, West Virginia University, Morgantown, WV. 362 pp.

Simmons, J., P. Ziemkiewicz, and D. Black. 2002. Use of steel slag leach beds for the treatment of acid mine drainage: the McCarty Highwall Project. p. 527-529. In: Proceedings, Nineteenth American Society for Surface Mining and Reclamation Conference, June 9-13, 2002, Lexington, KY.

Stark, L.R., F.M. Williams, S.E. Stevens, Jr., and D.P. Eddy. 1994. Iron retention and vegetative cover at the Simco constructed wetland: an appraisal through year eight of operation. p. 89-98. In: Proceedings, International Land Reclamation and Mine Drainage Conference, USDI, Bureau of Mines Special Publication SP 06A-94, April 24-29, 1994, Pittsburgh, PA

Sterner, P., J. Skousen, and J. Donovan. 1998. Geochemistry of laboratory anoxic limestone drains. p. 214-234. In: Proceedings, Fifteenth American Society for Surface Mining and Reclamation Conference, May 17-21, 1998, St. Louis, MO.

Thomas, R., and C. Romanek. 2002. Acid rock drainage in a vertical flow wetland I: acidity neutralization and alkalinity generation. p. 736-751. In: Proceedings, Nineteenth American Society for Surface Mining and Reclamation Conference, June 9-13, 2002, Lexington, KY.

Turner, D., and D. McCoy. 1990. Anoxic alkaline drain treatment system, a low cost acid mine drainage treatment alternative. In: Proceedings, 1990 National Symposium on Mining, University of Kentucky, Lexington, KY.

Tuttle, J.H., P.R. Dugan, C.B. MacMillan, and C.I. Randles. 1969. Microbial dissimilatory sulfur cycle in acid mine water. J. Bacteriology 97: 594-602.

U.S. Environmental Protection Agency. 1983. Neutralization of acid mine drainage. Design Manual. USEPA 600/2-83-001, Cincinnati, OH.

U.S. Environmental Protection Agency. 1995. Streams with fisheries impacted by acid mine drainage in Maryland, Ohio, Pennsylvania, Virginia and West Virginia. Region III. US EPA, Philadelphia. PA.

Vinci, B., and T. Schmidt. 2001. Passive periodic flushing technology for mine drainage treatment systems. p. 611-625. In: Proceedings, Eighteenth American Society for Surface Mining and Reclamation Conference, June 3-7, 2001, Albuquerque, NM.

Watzlaf, G.R., and R.S. Hedin. 1993. A method for predicting the alkalinity generated by anoxic limestone drains. In: Proceedings, Fourteenth Annual West Virginia Surface Mine Drainage Task Force Symposium, April 27-28, 1993, Morgantown, WV.

Watzlaf, G.R., C.L. Kairies, K.T. Schroeder, T. Danehy, and R. Beam. 2002. Quantitative results from the flushing of four reducing and alkalinity-producing systems. In: Proceedings, Twenty-Third West Virginia Surface Mine Drainage Task Force Symposium, April 16-17, 2002, Morgantown, WV.

Watzlaf, G.R., K.T. Schroeder, and C.L. Kairies. Long-term performance of anoxic limestone drains. Mine Water and the Environment 19:98-110.

Widdell, F. 1988. Microbiology and ecology of sulfate- and sulfur-reducing bacteria. p. 469-585. In: Biology of anaerobic organisms, A.J.B. Zehnder, ed. Wiley, New York,

Wieder, R.K., and G.E. Lang. 1982. Modification of acid mine drainage in a freshwater wetland. p. 43-53. In: Symposium on Wetlands of the Unglaciated Appalachian Region, West Virginia University, Morgantown, WV.

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

Younger, P. 2000. The adoption and adaptation of passive treatment technologies for mine waters in the United Kingdom. Mine Water and the Environment 19:84-97.

Ziemkiewicz, P.F., and D.L. Brant. 1996. The Casselman River Restoration Project. In: Proceedings, Eighteenth West Virginia Surface Mine Drainage Task Force Symposium, April 15-16, 1996, Morgantown, WV.

Ziemkiewicz, P.F., J.G. Skousen, and R. Lovett. 1994. Open limestone channels for treating acid mine drainage: a new look at an old idea. Green Lands 24(4):36-41.

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. 26:560-569.