Technical Article

Long-term Performance of Passive Acid Mine Drainage Treatment Systems

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Abstract. State and federal reclamation programs, mining operators, and citizen-based watershed organizations have constructed hundreds of passive systems in the eastern U.S. over the past 20 years to provide reliable, low cost, low maintenance mine water treatment in remote locations. While performance has been reported for individual systems, there has not been a comprehensive evaluation of the performance of each treatment type for a wide variety of conditions. We evaluated 83 systems: five types in eight states. Each system was monitored for influent and effluent flow, pH, net acidity, and metal concentrations. Performance was normalized among types by calculating acid load reductions and removals, and by converting construction cost, projected service life, and metric tonnes of acid load treated into cost per tonne of acid treated. Of the 83 systems, 82 reduced acid load. Average acid load reductions were 9.9 t/yr for open limestone channels (OLC), 10.1 t/yr for vertical flow wetlands (VFW), 11.9 t/yr for anaerobic wetlands (AnW), 16.6 t/yr for limestone leach beds (LSB), and 22.2 t/yr for anoxic limestone drains (ALD). Average costs for acid removal varied from $83/t/yr for ALDs to $527 for AnWs. Average acid removals were 25 g/m^2/day for AnWs, 62 g/m^2/day for VFWs, 22 g/day/t for OLCs, 28 g/day/t for LSBs, and 56 g/day/t for ALDs. It appears that the majority of passive systems are effective but there was wide variation within each system type, so improved reliability and efficiency are needed. This report is an initial step in determining passive treatment system performance; additional work is needed to refine system designs and monitoring.

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

Introduction

Upon exposure to water and oxygen, sulfide minerals commonly present in coal-bearing strata oxidize to form acidic, sulfate-rich drainage. Metal ion concentrations in acid mine drainage (AMD) depend on the type and quantity of sulfide minerals present as well as the host rock composition, but iron commonly dominates. Acidity in AMD consists of hydrogen ion acidity (measured as pH), mineral acidity (hydrolyzable Fe, Al, Mn concentrations), and dissolved carbon dioxide. The AMD chemistry is a function of site hydrology and contact with acid-producing (sulfide) and acid-neutralizing (carbonate) minerals (Skousen et al. 2002). In general, sulfide-rich and carbonate-poor sites produce acidic drainage, while carbonate-rich sites, even with significant sulfide concentrations, typically produce alkaline or neutral water.

Approximately 20,000 km of streams and rivers in the eastern United States are degraded by AMD (U.S. Environmental Protection Agency (EPA) 1995). About 90% of this AMD originates in abandoned underground coal mines. Since no company or individual claims responsibility for reclaiming abandoned mine lands (AML), 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 hydroxysulfates (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 neutralize the AMD with an alkaline reagent such as lime, caustic soda, soda ash, or ammonia, and collect the floc in ponds. Several reports are available that consider the site requirements, types of water, and costs for treating AMD with such chemicals (cf U.S.EPA 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 20 years, a variety of 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 and anaerobic wetlands, 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). Figure 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, aerobic wetlands can treat net alkaline water. Anoxic limestone drains can treat water with low Al, Fe^{3+}, and dissolved O_2 concentrations. Vertical flow wetlands, anaerobic wetlands, 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 (OH) and West Virginia (WV). 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 mines 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).

Wetlands are divided into two strategies for AMD treatment: 1) oxidizing or aerobic wetlands consist of *Typha* and other wetland vegetation planted in shallow (typically <30 cm) sediments comprised of soil, clay or mine spoil; and 2) reducing or anaerobic wetlands consist of *Typha* and other wetland vegetation planted in deep (generally >30 cm), organic substrates comprised of soil, peat moss, spent mushroom compost, sawdust, straw/manure, hay bales, or other organic

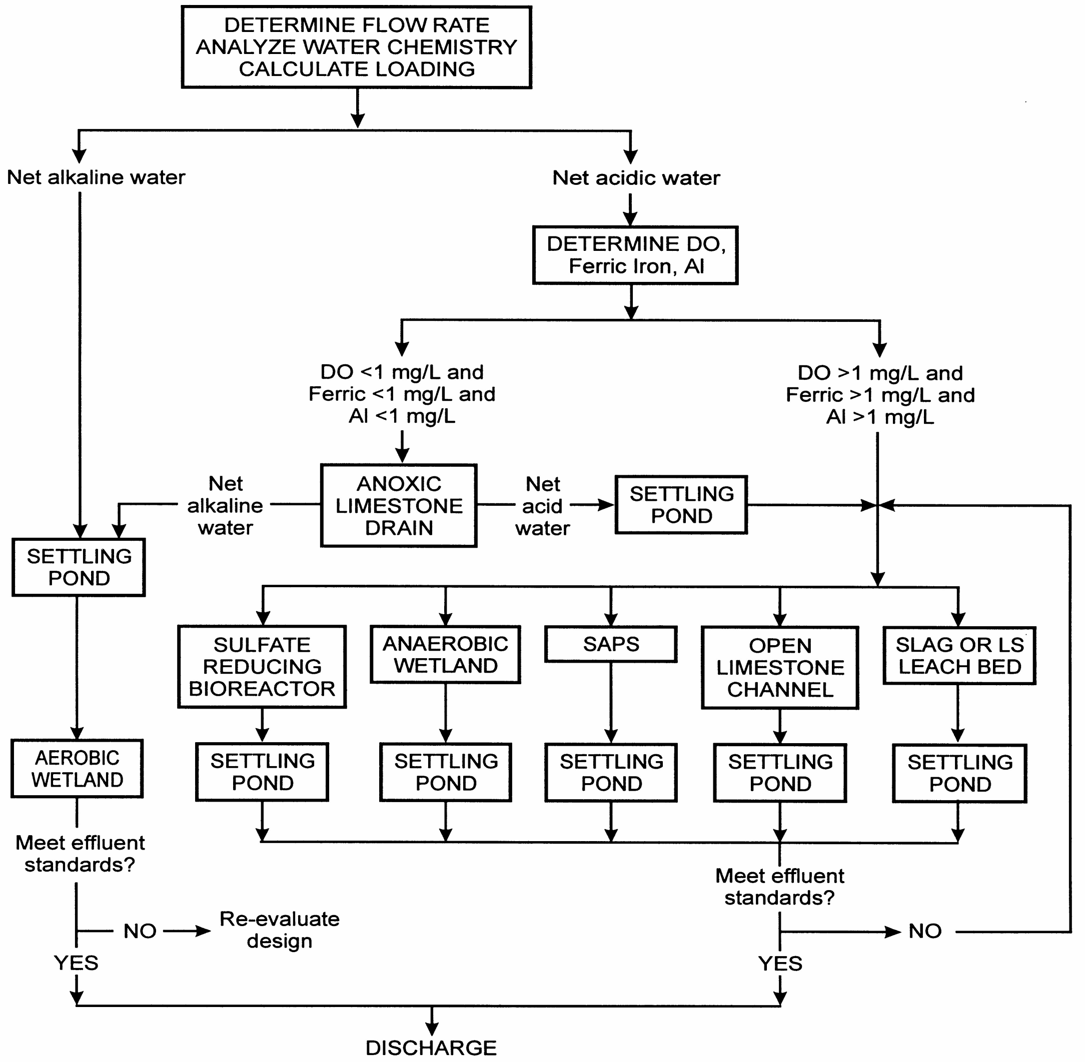

Figure 1. Diagram of possible passive treatment systems to treat mine water based on water flow and chemistry

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

System Type	Requirements	Construction	Design Factors	References
Aerobic Wetland	Net alkaline water	Overland flow; often planted with Typha	10-20 g Fe/m^2/day; 0.5-1 g Mn/m^2/day	Hedin et al. 1994a
Anaerobic Wetland (AnW)	Low flow, net acidic water	Flow over and within substrate	3.5 g acidity/m^2/day	Wildeman et al. 1993; Eger 1994; Hedin et al. 1994a; Watzlaf et al. 2000
Sulfate Reducing Bioreactor	Low flow, net acidic water	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, 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

mixtures. Both types often use limestone as a base or the limestone may be admixed 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.

Analysis of 73 sites in Pennsylvania (PA) suggested that constructed wetlands are the best available technology for many post-mining seeps of pH >5 (Hellier et al. 1994). 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, considering water quality.

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; 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). In addition, metals are precipitated as sulfides, hydroxides and/or carbonates (Henrot and Wieder 1990). Stark et al. (1994) reported long-term treatment of net acidic water by an anaerobic wetland with an adequate design, pH >5.5, and low metal concentrations. 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 (KY) (Karathanasis and Barton 1997), PA (Hellier 1996; Rose et al. 2001), and Tennessee (TN) (Schmidt and Sterns 2001). Like their aerobic counterparts, anaerobic wetlands must have substantial residence time for the water; therefore, they require large areas to treat large volumes of strongly acidic AMD. In mountainous areas, wetlands have been most successful when applied to small AMD flows of moderate water quality (Wieder 1993). 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, in that 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). Gusek (1998) reports successfully treating flows from 4 to 4,800 L/min and moderate to high acidity water with anaerobic bioreactors. Design criteria are usually based on a 24 to 36 hr retention time.

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. 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 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. The Howe Bridge and Morrison ALDs treat anoxic water; alkalinity increases by 128 and 248 mg/L, respectively, CO_2 pressures are near 0.1 atm, and calcite is at about 10% of saturation (Hedin et al. 1994a). At both sites, the water flows from an ALD to a wetland, where the iron oxidizes and precipitates; both systems are still functioning efficiently.

Service life is a concern with ALDs, given the tendency for Fe^{3+} and Al^{3+} hydroxides to plug the limestone bed (Nairn et al. 1991; Watzlaf et al. 2000). 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). They 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 first 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, about 1 m of acid water overlies 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) describe one VFW that reduced acidity from 320 to 93 mg/L and removed 2 mg/L ferric iron, another VFW that decreased acidity from 173 to 88 mg/L, and a third that decreased acidity from 84 to 5 mg/L, removed all (19 mg/L) ferric iron and discharged 1 mg/L ferrous iron. At another site, a VFW treated 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). The effluent from the VFW 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 VFWs, and cited a VFW that, with regular flushing, treated AMD containing 41 mg/L Al (c.f. Vinci and Schmidt 2001). Successful VFWs have used mushroom compost, while some VFWs with other types of organic material have had plugging problems (Nairn et al. 2000; Demchak et al. 2001; Gusek and Wildeman 2002); 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 still need to be investigated (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 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 OLCs 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 these passive treatment system types, and to assess their cost effectiveness in treating acidity.

Materials and Methods

Aerobic wetlands and sulfate reducing bioreactors were not evaluated in this study since one of the criteria that we used to compare the systems was acid load treated rather than metal removal. Forty-nine sites in seven eastern U.S. states (Alabama (AL), Indiana (IN), KY, Maryland (MD), OH, TN, and WV) with 83 separate treatment system types were chosen. The treatment units were between 2 and 12 years old at the time of final sampling. Data collected by state agencies were used to supplement data collected during the project so that sampling periods and water treatment assessments spanned several years. Information on the design, construction, and cost of each system was gathered from state and other 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. By measuring flow and chemistry in and out of each system type, the amount of acid removed by each component could be evaluated. Average net acidity concentrations both in and out are shown in table; where acid water became alkaline after treatment, the systems were reported as 100% acidity reductions.

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 acid concentration 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 multiplied by net acidity concentrations). Some sites had only one type of passive system installed on the site, while most of the sites had a combination of types. Removal efficiencies were also calculated for the systems and compared to design removal efficiencies. This was done by using the acid load treated and dividing by the size of the anaerobic wetlands or VFWs. Removal efficiencies were calculated for limestone systems by dividing acid load reductions (as tonnes of limestone) and converting to g of acid removed per day per tonne (g/day/t). Residence time of water was calculated for ALDs and LSBs based on limestone mass, 50% porosity, and influent flow.

Data analysis depended on estimating three key parameters: acid load treated, treatment unit construction cost, and service life. It was usually possible to obtain water samples upstream and downstream of the treatment units, but at some sites, construction methods precluded sampling upstream water quality. In these cases, we used pre-construction water quality. Acid load treated in a system was estimated as the difference between upstream and downstream water samples (flow and acidity).

The construction cost of each system was determined using contractor records. However, rarely was it possible to isolate the cost for an individual treatment unit within a site since so many other variable costs were included in the total reclamation cost of the site. Therefore, we standardized the cost of building an individual treatment unit by using 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, WV Dept of Environmental Protection, personal communication). Treatment unit dimensions were generally available, so we were able to calculate 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. This was estimated by the limestone consumption rate, which was calculated by dividing the limestone mass in the system by the annual acid load treated (then multiplying by 80% for the average neutralization potential of limestone). By this process, some units had an estimated service life of only two years, while a number of treatment units were removing acid load so slowly that the limestone supply would last for several hundred years. In fact, it was expected that these units would fail by some other means long before they exhausted the limestone. Therefore, we assigned a maximum service life of 20 years to all treatment units, since this is a common lifespan for passive system designs. Positive treatment was defined as less acid load coming out of the system than going in.

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. For example, an ALD may have been constructed to treat water with higher than optimal Al concentrations, which would compromise the system's performance. 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 for reasons other than those related directly to the system type, and our evaluation methodology would simply show a reduced effectiveness for that system.

Results

Anaerobic Wetlands: The 11 anaerobic wetlands showed wide variation in treatment (0.6 to 35.4 t/yr of acid load treated) and treatment costs (from \$138 to \$3,912/t/yr) (Table 2). Size varied from 40 to 5064 m^2 and removal rates ranged between 2.5 to 50.2 g/m^2/day. For example, the smallest system (WV-16b) of 40 m^2 removed acid at a rate of 37.3 g/m^2/day, while the two largest systems (WV-4b at 4740 m^2 and WV-6 at 5064 m^2) removed acid at around 15 to 18 g/m^2/day. All of the systems except for WV-1h (1568 m^2 and a removal rate of 2.5 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. This will be the case for all systems.

Anoxic Limestone Drains: The 28 ALDs gave a wide range of acid loads treated (between 0.3 to 130.9 t/yr), while costs ranged from \$34 to \$799/t/yr (Table 3). There was no apparent relationship between the pH of incoming water and the effectiveness of the ALD. Using a design factor of ≥15 hrs of residence time, the mass of limestone in the ALDs ranged from 90 to 6,930 t, and residence time ranged from 4 to 236 hrs. Most of the systems had residence times between 20 and 80 hrs (see comment above about initial sizing). The WV-28a site had a residence of 4 hrs, yet changed acidity concentration from 396 to 98 mg/L. The site with the longest residence time of 236 hrs, WV-35a, changed the acidity from 2389 to 1277 mg/L. There were only three systems that held the water for less than 15 hrs, yet all of these raised the pH to about 5.9 and neutralized acidity. We also calculated removal efficiency and found that these ALDs varied from 4.6 to 165.5 g/day/t, with an average of about 55.5 g/day/t. Assuming that the ALDs continue to 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 a surprising result, since many people assume that ALDs are prone to failure.

Vertical Flow Wetlands: Fifteen of 16 VFWs reduced acidity concentrations and acid loads. They showed wide variation in treatment cost, from \$39 at a MD site to \$2,023/t/yr at a WV site (Table 4). Sizes of VFWs ranged from 130 to 4156 m^2, and removal rates varied from 0 to 293 g/m^2/day. Two systems removed acid at a rate of >200 g/m^2/day, five removed acid at a rate between 40 to 117 g/m^2/day, and eight removed acid at a rate of 1.9 to 15 g/m^2/day. These removal rates are consistent with the design factor of 20 g/m^2/day.

Table 2. Influent and effluent characteristics, acid load treated, construction costs, removal efficiency (R.E.), and cost efficiency (C.E.) for anaerobic wetlands (AnW), assuming a service life of 20 years.

Site	N	Flow (L/s)	pH		Net Acidity (mg/L)		Acid Load Treated (t/yr)	Size (m^2)	Years in Service	Cost to Build ($)	R.E. ($g/m^2/day$)	C.E. ($/t/yr)
			In	Out	In	Out						
WV-4b	5	4.4	5.9	6.2	74	25	35.4	4,740	4	97,925	18.6	138
WV-1i	3	5.0	2.9	3.6	139	82	10.2	519	5	53,333	48.8	261
WV-34	20	1.7	2.9	2.9	1410	1040	24.4	1,412	10	150,219	42.9	308
WV-35b	8	0.9	2.5	2.6	1112	588	17.4	862	10	116,184	50.2	334
WV-16b	7	1.2	6.0	6.2	0	-15	0.6	40	4	4,947	37.3	412
WV-30k	9	0.6	4.6	5.2	231	96	2.4	223	5	20,000	26.8	417
WV-30l	8	0.6	4.3	6.0	83	-2	1.2	297	5	20,000	10.0	833
WV-6	63	10.9	3.0	4.9	259	81	31.3	5,064	7	549,901	15.4	878
WV-29	6	1.9	3.0	3.7	147	90	3.2	812	10	97,143	9.8	1,518
WV-25b	11	0.4	2.9	3.4	357	239	3.8	1,185	10	152,375	7.9	2,005
WV-1h	3	0.6	3.0	4.6	134	45	1.6	1,568	5	125,187	2.5	3,912

Table 3. Influent and effluent characteristics, acid load treated, construction costs, residence time (R.T.) removal efficiency (R.E.), and cost efficiency (C.E.) for anoxic limestone drains (ALD)

Site	N	Flow (L/s)	pH		Net Acidity (mg/L)		Acid Load Treated (t/yr)	Size (t)	Years in Service	Cost to Build ($)	Est. Service Life (yrs)	R.T. (>15 hrs)	R.E. (g/day/t)	C.E. ($/t/yr)
			In	Out	In	Out								
WV-26	5	0.1	3.0	6.6	1515	-41	6.7	128	8	3,488	15	100	143.4	34
WV-30b	5	0.6	6.3	6.6	50	-214	4.7	123	5	3,321	20	16	104.7	35
WV-32	6	0.4	2.9	4.9	1064	340	8.0	215	4	5,747	20	42	102.0	36
WV-1a	3	12.9	3.7	6.8	96	-186	130.9	4,267	5	115,207	20	26	84.1	44
OH-1c	8	1.7	2.9	4.7	712	157	20.1	720	2	18,154	20	33	76.5	45
WV-28b	5	1.5	3.1	5.8	591	226	15.1	250	9	2,656	3	13	165.6	59
WV-19a	4	0.4	3.3	6.9	1020	-210	19.5	972	3	26,301	20	191	55.0	67
WV-7e	5	3.7	4.1	6.3	66	-157	125.6	6,285	3	169,695	20	133	54.8	68
WV-1b	3	11.9	3.7	6.6	96	-195	121.4	6,222	5	167,994	20	41	53.5	69
WV-2c	4	2.3	4.1	6.3	307	-53	29.4	1,583	4	42,743	20	54	50.9	73
WV-28a	10	1.9	3.0	5.7	396	98	4.6	97	9	6,829	20	4	129.9	74
WV-4a	4	3.0	2.9	5.9	405	74	7.1	409	4	11,041	20	11	47.6	78
WV-22a	6	0.4	2.7	6.5	730	-168	11.0	652	5	17,299	20	128	46.2	79
WV-1d	3	1.9	3.7	6.1	96	-37	8.8	517	5	13,957	20	21	46.6	79
MD-3a	7	1.0	5.8	6.4	299	73	13.2	770	5	20,790	20	60	47.0	79
WV-30g	7	0.3	2.9	6.3	631	14	5.1	315	5	8,505	20	82	44.4	83
WV-19b	4	0.3	3.3	6.5	1020	188	10.3	702	3	19,050	20	184	40.2	92
WV-8a	20	1.5	3.5	5.5	668	594	17.8	1,265	5	34,208	20	66	38.6	96
WV-5	2	3.8	3.8	5.8	79	10	9.3	955	2	25,783	20	20	26.7	139
WV-30e	6	0.3	4.3	5.8	88	-38	0.8	90	5	2,430	20	24	24.4	152
WV-30c	4	0.1	6.5	6.5	146	-138	0.9	108	5	2,916	20	85	22.8	162
WV-30a	7	0.2	5.2	6.7	139	-93	1.3	276	5	7,452	20	108	12.9	287
WV-8b	29	0.8	3.4	5.9	718	648	4.3	940	5	25,099	20	92	12.5	292
WV-16a	7	1.0	3.3	6.2	201	-107	4.3	1,194	4	32,238	20	94	9.9	374
WV-30d	5	0.1	6.3	6.3	216	117	0.3	110	5	2,969	20	86	7.5	495
WV-17	19	2.6	3.1	7.0	131	-59	18.8	6,930	12	187,110	20	209	7.4	498
WV-35a	8	0.2	2.9	5.9	2389	1277	20.8	600	1	15,903	1	236	95.0	546
WV-1c	3	0.6	3.7	6.3	98	-25	2.5	1,480	5	39,961	20	194	4.6	799

Table 4. Influent and effluent characteristics, acid load treated, construction costs, removal efficiency (R.E.), and cost efficiency (C.E.) for vertical flow wetlands (VFW); the service life for the systems was estimated at 20 years, with the exception of the last site, for which no such data was available.

Site	N	Flow (L/s)	pH		Net Acidity		Acid Load Treated (t/yr)	Size (m^2)	Years in Service	Cost to Build ($)	R.E. ($g/m^2/day$)	C.E. ($/t/yr)
			In	Out	In	Out						
					(mg/L)							
MD-1c	7	1.7	2.8	6.7	841	-215	21.8	185	3	16,880	293.2	39
KY-1	16	2.3	2.8	5.1	843	22	68.7	800	1	74,046	213.2	54
WV-3a	6	0.7	3.0	6.3	141	-125	8.7	185	3	14,313	117.0	82
MD-1a	7	0.4	6.1	7.2	365	83	5.0	130	3	12,771	95.7	128
OH-1b	8	2.0	3.4	6.9	176	-99	21.2	590	2	58,945	89.4	139
OH-2a	6	0.9	3.6	6.0	127	81	6.8	200	1	19,898	84.6	146
WV-3b	6	0.3	2.9	6.0	195	-117	3.4	204	3	15,753	41.5	232
MD-2b	3	1.0	6.7	7.1	-20	-109	4.0	650	3	43,878	15.3	548
WV-15c	2	0.4	2.7	6.3	499	185	4.3	1,493	3	56,878	7.2	661
WV-7f	5	0.6	5.8	6.6	18	-237	6.1	1,484	3	89,314	10.2	732
WV-3c	5	0.1	3.0	5.1	134	0	0.6	148	3	11,461	10.1	955
MD-3c	7	1.0	6.7	6.7	24	6	1.5	584	3	39,907	6.4	1,330
WV-16e	7	1.2	6.2	6.4	-20	-32	0.4	148	4	11,208	6.7	1,401
WV-1g	3	1.2	3.4	6.8	53	-62	5.9	3,061	5	213,267	4.8	1,807
WV-15d	2	0.4	4.9	6.9	134	-89	3.1	4,156	3	125,406	1.9	2,023
OH-2d	6	0.9	6.8	6.8	13	14	0.0	150	1	14,486	0	na

Table 5. Influent and effluent characteristics, acid load treated, construction costs, removal efficiency (R.E.), and cost efficiency (C.E.) for open limestone channels (OLC)

Site	N	Flow (L/s)	pH		Net Acidity		Acid Load Treated (t/yr)	Size (t)	Years in Service	Cost to Build ($)	Est. Service Life (yrs)	R.E. (g/day/t)	C.E. ($/t/yr)
			In	Out	In	Out							
					(mg/L)								
IN-2b	49	4.7	4.8	5.3	230	150	13.2	40	2	950	3	904.2	24
WV-14	3	10.9	3.7	3.9	212	141	24.1	889	6	24,004	20	74.3	50
WV-31	6	1.3	2.9	4.5	692	55	25.0	2,711	4	73,184	20	25.3	146
WV-24	3	11.9	4.0	5.5	41	7	14.2	1,785	2	46,272	20	21.8	163
WV-12c	6	12.2	4.2	5.5	76	56	8.6	892	2	28,099	20	26.4	163
WV-36b	35	9.9	5.6	6.0	8	2	2.8	450	1	11,250	20	17.0	201
WV-36a	35	41.7	5.7	5.5	20	10	1.7	300	3	7,500	20	15.5	221
WV-11	2	1.8	2.5	2.6	849	727	6.8	1,248	3	36,192	20	14.9	266
WV-12b	6	2.1	3.5	5.3	66	30	2.8	1,170	2	31,590	20	6.6	564
WV-33c	6	0.3	5.1	5.5	28	12	0.1	600	5	15,046	20	0.4	7,523

Open Limestone Channels: Ten OLCs were evaluated, and all reduced acidity and showed some acid load reduction (Table 5). The cost of treatment varied between 24 and $7,523/t/yr. Except for WV-33c, all treated water at or less than $500/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 based on g/day/t. One site was incredibly efficient at >900 g/day/t, but most were around 15 to 20 g/day/t. Without the outlier, the average removal was 22.4 g/day/t.

Limestone Leach Beds: Limestone beds have been extensively installed in AL and TN. All 18 systems reduced acidity (Table 6). The LSBs removed between 0.4 to 59 t/yr of acid load and some did so at very low cost. Using the same technique for calculating residence time as ALDs, the mass of limestone in these LSBs ranged from 150 to 6250 t, and the residence time of these systems varied between 0.3 and 818 hrs, with most being between 10 and 70 hrs. All of them, except WV-36c (with a residence time of 0.3 hrs), had greater than 1.5 hrs of residence time. Like OLCs, one of the LSBs had an extremely high removal efficiency, but all

Table 6. Influent and effluent characteristics, acid load treated, construction costs, removal efficiency (R.E.), and cost efficiency (C.E.) for limestone leach beds (LSB)

Site	N	Flow (L/s)	pH		Net Acidity (mg/L)		Acid Load Treated (t/yr)	Size (t)	Years in Service	Cost to Build ($)	Est. Service Life (yrs)	Residence Time (>15 hrs)	R.E. (g/day/t)	C.E. ($/t/yr)
			In	Out	In	Out								
WV-36c	3	36.7	5.7	4.4	19	10	10.9	150	3	3,750	11	0.3	199.1	31
TN-1c	7	22.1	2.9	4.0	93	48	58.9	2,996	6	74,911	20	11	53.9	64
WV-13a	3	0.4	3.1	6.0	432	-100	7.2	523	5	14,122	20	103	37.7	98
TN-1d	7	19.1	3.0	5.4	118	28	44.0	3,737	2	93,436	20	15	32.3	105
IN-2a	4	4.7	2.7	4.8	515	230	47.1	4,000	2	100,000	20	67	32.3	106
WV-13b	3	0.9	2.8	3.1	646	432	6.6	523	5	14,122	20	46	34.5	107
TN-2c	5	2.3	2.3	3.4	701	293	32.3	4,800	4	120,000	20	164	18.4	186
TN-1b	7	16.4	3.1	5.0	71	17	24.4	3,960	3	98,989	20	19	16.7	203
TN-2d	5	0.9	2.6	3.5	359	103	7.6	4,530	3	113,437	20	395	4.6	221
TN-2b	5	6.3	2.5	3.3	286	177	24.1	4,740	6	113,783	20	59	13.9	236
AL-1	4	1.6	3.8	7.5	92	-42	7.4	1,490	1	35,825	20	73	13.6	242
WV-9	3	0.2	3.3	7.0	262	-46	2.0	414	4	10,350	20	163	13.2	259
WV-36d	3	11.8	5.6	4.4	8	-7	4.6	1,500	1	37,500	20	10	8.4	408
AL-2c	2	5.1	3.9	7.6	26	-33	10.6	4,210	4	100,997	20	65	6.9	476
AL-2a	2	2.8	6.7	7.6	-28	-56	3.6	1,560	4	37,667	20	44	6.3	523
TN-1a	7	1.6	3.2	6.2	70	-44	6.7	4,375	4	104,991	20	215	4.2	784
AL-2b	2	7.3	7.0	6.8	-29	-72	0.4	730	4	17,527	20	8	1.5	2,191
TN-2a	5	0.6	2.9	4.1	245	188	1.3	6,250	8	150,530	20	818	0.6	5,790

the rest were <50 g/day/t with an average of 17.6 g/day/t without the outlier. These, along with ALDs, were among the most efficient systems in this study.

Slag Leach Beds: Slag leach beds are a new technology and only two were available for evaluation (no table). They were in place for only 1 or 2 years at the time of monitoring. One system reduced the net acidity of a 6.5 L/s flow from 46 to –37 mg/L, treating about 19 t/yr of acid at a cost of $84/t/yr. The other site reduced the net acidity of an extremely large flow (68 L/s) from 173 to 72 mg/L at a cost of $256/t/yr. Removal efficiencies were 24.4 and 8.0 g/day/t. The sample size and relatively recent construction advise caution in interpreting the results. Nonetheless, both projects reduced the acidity concentrations and the acid load.

Summary

Passive system designers and reclamation planners need to know which system types provide the greatest return per dollar and general removal efficiencies. This analysis was a first attempt at evaluating performance across a variety of system types and a wide range of water flows and qualities. We evaluated AMD treatment by 83 passive system units ranging in age from 1 to 12 years. Reductions in acidity concentrations and acid load were measured at 82 of the 83 sites. Table 7 summarizes the performance of the various treatment technologies based on successful treatment. Given that the number of treatment units per technology ranged from 2 to 28, the performance average values are not directly comparable, but provide an indication of the positive treatment results with these passive treatment system types. Average amounts of acid treated ranged from 9.9 t/yr for OLCs to 22.2 t/yr for ALDs.

The average cost per t/yr of acid removed ranged from $83 for ALDs to $527 for anaerobic wetlands (Table 7). Anaerobic wetlands had the highest average construction cost, but this 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 cost of treatment to $417. 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. Anaerobic wetlands removed acidity at a rate of 2.5 to 50 g/m^2/day (compared to the design factor of 2.5), and VFWs removed acidity at rates that ranged up to 293 g/m^2/day (compared to a design factor of 20). Residence times of >15 hrs also appear to be adequate for acidity reductions in ALDs and LSBs. Removal efficiencies for ALDs, OLCs, and LSBs ranged from 20 to 50 g/day/t.

Table 7. Summary of the treatment effectiveness of passive treatment systems

System Type	Number of Units	Number Positive	Average Total Cost ($)	Average Acid Treated (t/yr)	Average Removal and Residence Time (g/day/t, hrs, $g/m^2/day$)	Average Cost ($/t/yr)
ALD	28	28	$36,744	22.2	55.5 g/day/t, 84 hrs	83
OLC	10	10	$27,409	9.9	22.4 g/day/t	138
LSB	18	18	$68,997	16.6	27.7 g/day/t, 126 hrs	207
VFW	16	15	$51,151	10.1	62.3 $g/m^2/day$	253
AnW	11	11	$126,110	11.9	24.5 $g/m^2/day$	527
Total:	83	82				

It is hoped that further analysis and monitoring of passive systems will help planners to refine designs and installation procedures.

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