




Passive Treatment of Acidic Coal Mine Drainage: The Anna S Mine Passive Treatment Complex

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Abstract The Anna S coal mine complex in Tioga County, PA, produces drainage with a pH of 2.8–3.6 and contains 3–36 mg/L Al, 1–36 mg/L Fe, and 6–9 mg/L Mn. In 2003, the Babb Creek Watershed Association installed two systems that passively treat three discharges from the acid mine drainage (AMD) severely degraded Babb Creek mine complex. Both systems contain four parallel vertical flow ponds followed by aerobic wetlands. The vertical flow ponds contain a total of 35,483 t of limestone and 4,973 m³ of organic substrate. During the last 6 years, the systems have treated an average of 1,971 L/min of flow to neutral form with 135–146 mg/L of alkalinity (as CaCO₃) with less than 1 mg/L of Al and Fe, and 2–4 mg/L of Mn. The vertical flow ponds have generated alkalinity at rates of 32–53 g/m²/day as CaCO₃. No seasonal variation in treatment effectiveness has been observed, despite relatively harsh winter seasons. The total cost of the passive systems was \$2.5 million (US). The 20 year projected unit treatment cost, including periodic replacement of the organic substrate, is \$403–618 per t (as CaCO₃) net alkalinity generated.

Keywords Acid mine drainage Passive treatment Coal mining

Introduction

The Babb Creek watershed in north-central Pennsylvania contains bituminous coal deposits that were widely mined by underground and surface activities in the late 1800 and

Background

The Anna S Mine Complex in southern Tioga County, Pennsylvania (USA). The mine complex and the treatment system described here are visible on Google Earth at 41°37'09.75"N, 77°19'20.97"W. The core of the complex is an abandoned 340 ha underground room and pillar mine that was developed between 1880 and 1920 in the Bloss

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bituminous coal seam. Shallow coal along the outcrop was Fe, Al, and Mn by inductively coupled plasma spectrometry. Samples were not filtered prior to acidification and the results represent total metal concentrations. In 2004 and 2005, laboratory analyses were conducted by the Pennsylvania State Laboratory, which is managed by the PADEP. Since 2006, analyses have been conducted by G&C Laboratories of Summerville, PA.

The mine has produced several large discharges for Mine discharge flow rates were measured between 1977 and 1989 at weirs installed by the USGS and between 1997 and 1999 at weirs installed by HE. After installation of the tunnel and its discharge are known as Hunters Drift and will be referred to as 'HD' in this paper. The central portion of the pipes discharging AMD into the systems. Pipe flows were measured by the timed-volume method.

This discharge is known as Anna S1 and will be referred to as 'S1'. During surface mining, a discharge developed between HD and S1 that is known as Anna S2, referred to herein as 'S2'. The passive treatment systems described in this paper treat these three discharges.

The northern portion of the mine complex discharges through collapsed and back filled entries referred to as the Mitchell discharges. The Mitchell discharges were not treated by the passive system complex described here. The deep mine discharges increased substantially when the complex was disturbed by surface mining in the early 1980s, but have been decreasing since.

Discharge Sampling

The mine discharges have been sampled for the last 35 years through several monitoring efforts. In 1975 and 1976, the discharges were monitored as part of Pennsylvania's Operation Scarlift (Boyer Kantz and Associates 1976). Between 1977 and 1984, the United States Geological Survey (USGS) made monthly measurements of flow and chemistry for the HD and S1 discharges (Reed 1980). Between 1984 and 1989, a local mining company monitored the HD, S1, and S2 discharges. Between 1996 and 1998, the Pennsylvania Dept of Environmental Protection (PADEP) and Hedin Environmental (HE) monitored flow and chemistry for HD, S1, and S2. The mine discharges and passive treatment systems were monitored by BCWA and HE between 2004 and 2010.

Sampling Methods

Sampling and analytical methodologies presented herein pertain to samples collected since the system was constructed in 2004. Field measurements were made of pH and temperature using a calibrated electronic pH meter. Alkalinity was measured in the field by titration with 1.6 N sulfuric acid to pH 4.5. A raw sample was analyzed in laboratory for pH, alkalinity, hot acidity, sulfate, and total suspended solids by standard methods (APHA 1999). Field measurements of pH and alkalinity were used in preference to laboratory values, when available. An acidified sample (50% nitric acid) was analyzed for total concentrations of

Table 1 Average chemical characteristics of untreated discharges from the Anna S Mine Complex (concentrations in mg/L)

Period	Source	n	pH	Acid	Fe	Al	Mn	SQ
Hunters drift (HD)								
1975–1976	Boyer Kantz	12	2.8	348	38	NA	NA	477
1977–1978	USGS, pre-SM	10	2.7	370	39	NA	4	474
1978–1984	USGS, post-SM	64	2.8	1,119	135	NA	23	1,371
1985–1989	Antrim mining	75	2.7	874	91	74	24	1,132
1996–1998	PADEP & HE	28	2.8	491	44	36	10	715
2004–2010	BCWA & HE	20	2.8	368	37	36	7	552
Anna S1 (S1)								
1975–1976	Boyer Kantz	12	3.1	212	11	NA	NA	348
1977–1978	USGS, pre-SM	10	2.8	225	15	NA	4	331
1978–1984	USGS, post-SM	66	2.9	550	31	NA	12	665
1985–1989	Antrim mining	73	2.9	408	43	33	22	725
1996–1998	PADEP & HE	28	3.0	271	12	16	14	542
2004–2010	BCWA & HE	13	3.0	165	8	13	9	367
Anna S2 (S2)								
1975–1976	Boyer Kantz	12	3.8	39	<1	NA	NA	96
1980–1984	Antrim mining	17	3.5	176	3	NA	4	186
1989–1991	Antrim mining	26	3.0	294	20	15	21	639
1996–1998	PADEP & HE	27	3.2	140	2	7	8	286
2004–2010	BCWA & HE	11	3.7	47	1	3	5	150

n = sample size; acidity as CaCO₃ 'NA' indicates that data were not available

^a Pre-surface mining, which daylighted portions of the deep mine complex

water owing into the transfer pipe. Flows exceeding the approximately the 90th percentile loading conditions of limit are bypassed around the treatment systems. Each the S1 and S2 discharges. The lower bench was not large transfer pipe connects to a distribution structure that creates enough to satisfy these design goals for the HD system. The individual ows that are piped to speci c VFPs. The S1 largest series of VFPs that could be t on the lower bench discharge is divided into four ows that are piped to VFP1, were suitable for treatment of the 50th percentile ows and VFP2, VFP3, and VFP4. The S2 discharge is divided into loadings (as assessed in 2000). The design was implemented two ows that are piped to VFP1 and VFP3. The HD dis- with a plan to adjust the ow rates to the HD system after charge is divided into four ows that are piped to VFP5, installation and determination of treatment effectiveness. VFP6, VFP7, and VFP8. The distribution structures are Figure 3 is a typical cross-section of the VFP units. Each designed so that the amount of water owing to each VFP contained 1 m of AASHTO #1 limestone aggregate (89% can be modi ed.

The size of the systems was based on acidity loadings, the organic substrate was a mixture of 50% spent mushroom predicted acidity removal rates, and site constraints room compost, 25% wood chips, and 25% AASHTO #10 Acidity loadings were calculated as grams per day (g/day) limestone (volume percentages). Flow out of each VFP is from the product of average in uent acidity concentration collected by a pipe underdrain placed at the bottom of the and the design ow rate. The predicted acidity removal rate aggregate, and is connected to the ef uent pipe through a was 50 g/m²/day. The preferred sizing for the VFPs was water level control structure. The water level control box calculated from the loading and removal rates, as follows contains removable panels that can be used to manipulate the water elevation within each VFP.

$$\text{VFP size (m}^2) = \frac{1}{4} \frac{\text{Acidity loading (g/day)}}{\text{Acidity removal (g/m}^2\text{/day)}}$$

Table 2 shows the size and materials for the treatment units in each installed system. All eight VFPs were rectangular and approximately the same size. On average, the

The sizing of the VFPs was affected by site constraints VFPs were 3,368 m² at the design water surface (0.6 m The design goal for both systems was to treat the 75–90th above the organic substrate) and contained 3,943 metric percentile ows and acidity loadings. The upper bench was tons (t) of limestone aggregate overlain with 614 of large enough to accommodate four VFPs sized for organic substrate amended with 493 t of limestone nes.

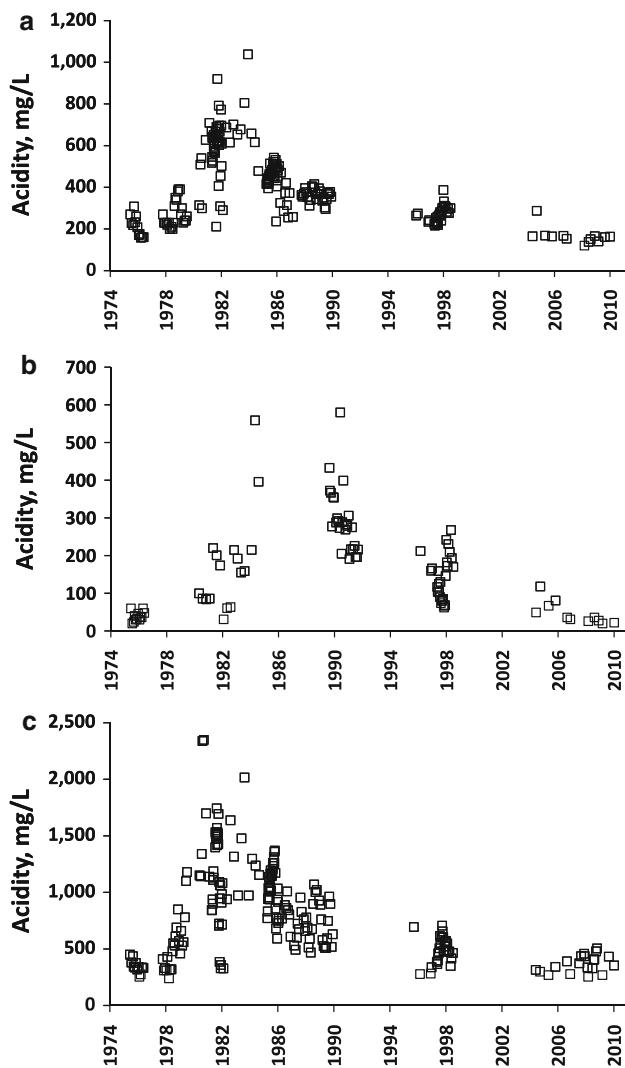


Fig. 1 Acidity concentrations since the 1970's for a the S1 discharge; b the S2 discharge; c the HD discharge

The average theoretical retention time of AMD was 174 h in the Anna VFPs and 245 h in the HD VFPs.

The VFPs were constructed with a flushing system that allows water to be rapidly withdrawn from the top of the limestone bed. The design of the flushing system followed Weaver et al. (2004) and had a calculated flush velocity, V_s , of 10^{-3} m sec^{-1} . This value is in the low range of that considered minimally feasible for effective flushing of solids from limestone aggregate by Weaver et al. (2004).

Results

Treatment Effectiveness

Table 3 shows average chemical conditions and flow rates for the inlets of both systems, the combined VFP area of the VFP. The Anna system received a higher

flow rate, and the inlet flow rate. Figure 4 shows alkaline and acidic characteristics of the system flow rate throughout the 5 years of operation. The inlet discharges of both systems were always alkaline with pH greater than 6.5. Fe and Al concentrations were each 1 mg/L except on one occasion when the Anna inlet discharge was reported to contain 4 mg/L Fe and 4 mg/L Al. These values are suspected to be erroneous.

Both systems produced a net discharge with 100–200 mg/L alkalinity and removed all the acidity associated with Al and Fe. Because the HD discharge contained more contaminated water, the HD system generated substantially more net alkalinity (inlet acidity minus outlet acidity) than the Anna system. On average, the HD system generated 481 mg/L net alkalinity while the Anna system generated 261 mg/L net alkalinity.

Figures 5 and 6 show the chemical characteristics of the VFP flow rate. The flow rate of the VFPs were always net alkaline (Fig. 5). The VFPs removed all of the inlet Al, a portion of the Fe, and little of the Mn (Fig. 6). Subsequent aerobic flow through ditches and wetlands removed all of the Fe and 60% of the Mn. The oxidative metal-removal processes generate acidity, which resulted in outlet alkalinity concentrations lower than the VFP flow rate.

All net acidity removal occurred in the VFPs through a combination of acidity neutralization and alkalinity generation. The two primary processes that generate alkalinity in passive mine water treatment systems are calcite dissolution and bacterial sulfate reduction (Hedin et al. 1994; Younger et al. 2002). Calcite dissolution increases Ca concentrations while sulfate reduction decreases sulfate concentrations. Calcium was not included in the monitoring program. The VFPs in both systems had minimal effect on sulfate concentrations (Table 4), indicating that bacterial sulfate reduction was not an important source of alkalinity, and that the major source of net alkalinity generation was limestone dissolution. Table 4 shows the sum of the calculated CaCO₃ equivalents agree to within 10% with the measured changes in acidity. The HD system, which received more acidic and metal-contaminated water, exceeded the Anna system in each acidity neutralization component. In both systems, Al removal was the largest source of acidity removal, followed by H⁺ and Fe removal.

Rates of Acidity Removal by the VFPs

Table 5 shows flow and acidity removal for each VFP. Removal was measured from changes in concentration and also changes in loadings that were adjusted for the surface area of the VFP. The Anna system received a higher

Fig. 2 Layout of the passive treatment systems

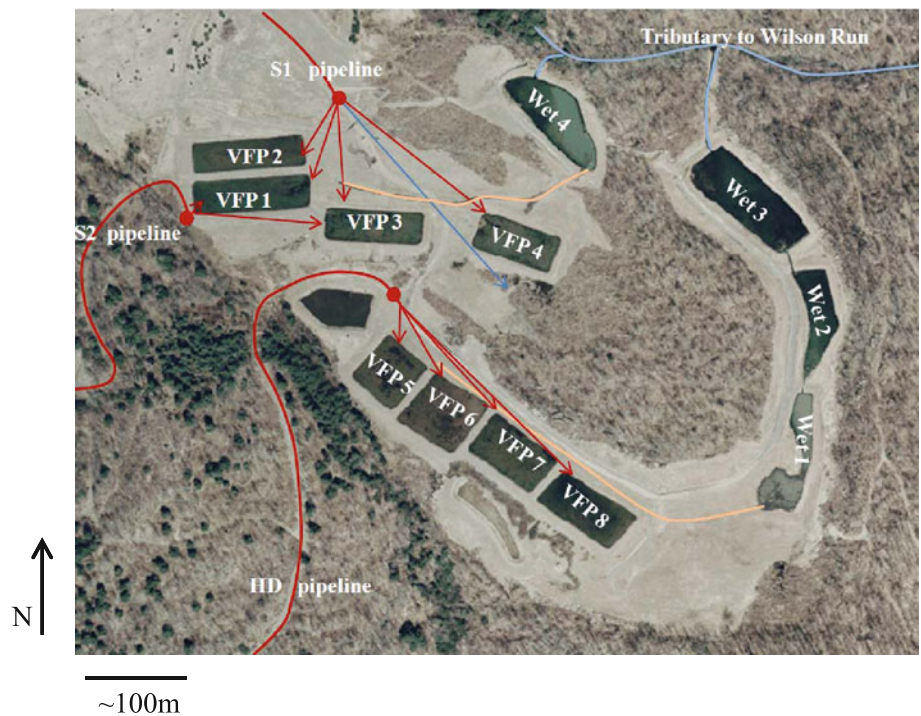
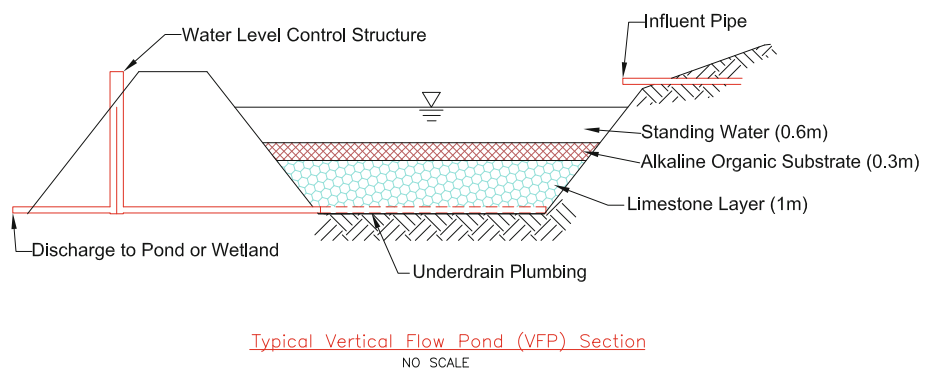


Fig. 3 Typical cross section of the vertical flow ponds



hydrologic loading but a lower acidity loading because the color and smell so that the mine water was less contaminated than the HD. Acidity loadings were not as high as expected during the design because the influent chemistry has moderated since the system was designed in 2000 (see Table 1). The Anna VFPs generated 31–41 g/day and the HD VFPs generated 46–52 g/day.

Temporal Changes in Treatment Effectiveness

During the first 6–12 months, both systems discharged water with very high alkalinity and low concentrations of Fe and Al. The VFP discharges were discolored (brown) and smelled of hydrogen sulfide, and generated foam after aeration. The ditches and wetlands effectively eliminated the color and smell so that the mine discharges from the two systems were clear and odorless. Discolored foamy water was not observed after the first year. No decay in the effluent quality of the Anna system is apparent after 6 years (Fig. 6). For the last 4 years, the effluent has maintained 90–140 mg/L alkalinity. The HD system has also maintained an alkaline condition over the 6 year period, though a decline in alkalinity generation is apparent. The effluent alkalinity decreased from 150 to 200 mg/L alkalinity in the first 2 years to 100–150 mg/L alkalinity during the last 3 years. The source of this change was increased concentrations of Fe in the VFP effluents (Fig. 6). In 2004 and 2005, the HD VFPs always discharged water with an average of 4 mg/L of Fe. In 2008, the average HD VFP effluent contained 36 mg/L of Fe. The 32 mg/L increase in Fe has an acidity equivalency of 50 mg/L, which is approximately the loss of alkalinity.

Table 2 Surface areas and substrate quantities for the treatment uni

	Surface area (m ²)	LS layer (t) ^a	Organic substrate	
			Organic, m ³	LS, t
Anna system				
VFP1	3,486	4,128	637	512
VFP2	3,227	3,663	587	472
VFP3	3,029	3,514	544	436
VFP4	3,211	3,437	542	435
Wetland 4	4,343	0	0	0
HD system				
VFP5	2,935	3,478	543	436
VFP6	3,799	4,623	710	571
VFP7	3,466	4,136	641	515
VFP8	3,795	4,562	706	567
Wetland 1	3,283	0	0	0
Wetland 2	2,483	0	0	0
Wetland 3	4,092	0	0	0

^a LS limestone

Table 3 Average treatment performance by the HD and Anna pas

	Flow L/min	pH	Alk mg/L	Acid mg/L	CaCO ₃	Fe mg/L	Al mg/L	Mn mg/L	SO ₄
Anna passive system									
S1 in ow	912	3.0	0	165	8	13	9	367	
S2 in ow	151	3.7	0	47	1	3	5	150	
VFP ef uent	NA	6.9	150	-108	3	<1	7	350	
Final ef uent	NA	7.3	135	-95	<1	<1	4	335	
HD passive system									
HD in ow	908	2.8	0	368	37	36	7	552	
VFP ef uent	NA	6.8	180	-117	24	<1	7	564	
Final ef uent	NA	7.4	146	-112	<1	<1	2	499	

The downward trend in alkalinity generation and the increased concentrations of Fe in the HD VFP ef uents are considered indicators that the organic substrate is becoming less reactive. In August 2009, the HD VFPs were individually drained and the organic substrates were mixed. Ef uent samples collected in January 2010 had alkalinity and net acidity concentrations similar to 2004–2006 values (Fig 4 and 5).

Seasonal Variation in Treatment Effectiveness

The Anna S passive systems are located in north-central Pennsylvania, which has a temperate climate that includes large seasonal temperature variation. Summer daytime temperatures are 20–30 C. During winter, temperatures fall to -15 C and it is common for air temperatures to stay below 0 C continuously for weeks. Despite major seasonal variation in air temperatures, no seasonal variation in treatment effectiveness was observed. Table 3 shows average annual ef uent chemical parameters for the two

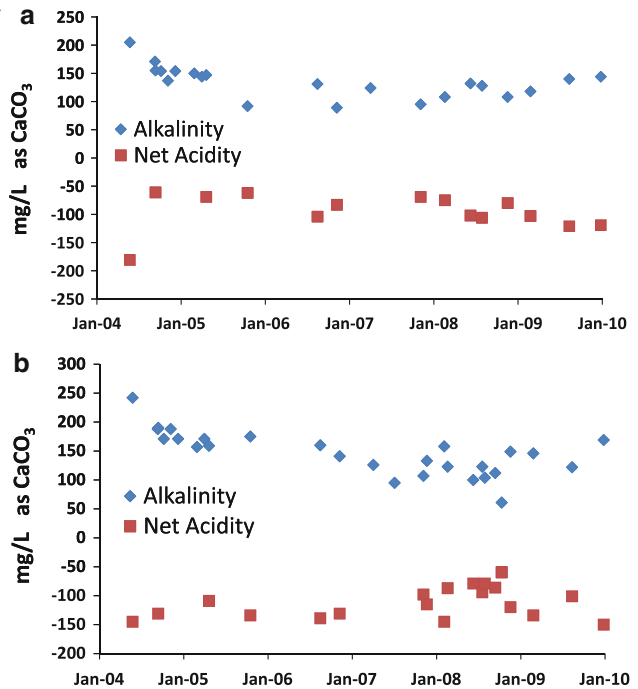


Fig. 4 Concentrations of alkalinity and net acidity at the annual discharges of the Anna and HD systems

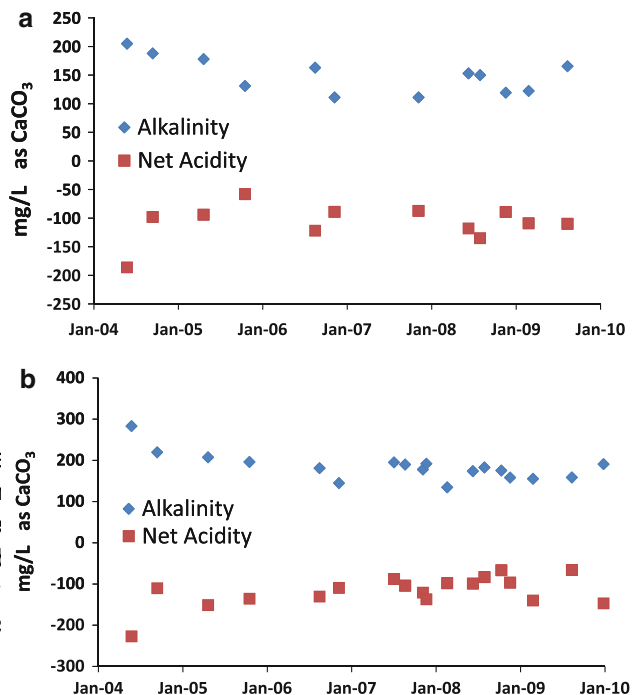


Fig. 5 Concentrations of alkalinity and net acidity for the VFP discharges of the Anna and HD systems

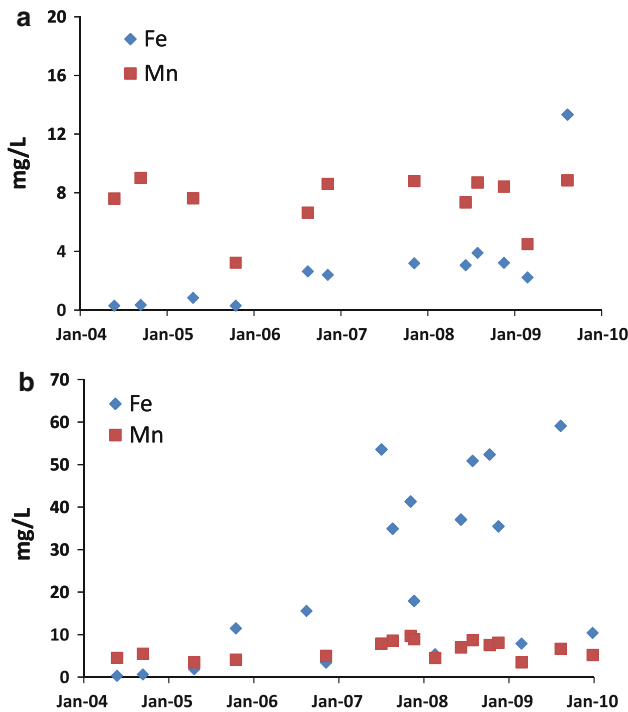


Fig. 6 Concentrations of Fe and Mn for the VFP discharges of the Anna and HD systems

systems in warm and cold months; the treatment differences were negligible.

System Head Losses

The head losses within the VFPs were measured in March 2004, several months after system construction, and again in November 2006, after almost 3 years of operation. Head losses were all less than 2.5 cm when the system was newly constructed. After 3 years of system operation, the

head losses for the VFPs were still less than 5 cm. No head loss measurements were made in years 4–6 because no changes in water elevations in the VFPs were apparent.

Operation and Maintenance (O & M)

The treatment systems have been maintained since their construction by the Babb Creek Watershed Association (BCWA). Routine operational activities include bi-monthly system inspections, water sampling every 6 months, VFPushing every 6 months, and the cleanout of overgrown ditches every couple of years. These routine activities require approximately 90 man-hours per year and had total cost in 2009 of approximately \$4,600/year. In addition to these routine activities, several maintenances activities have been necessary, including:

- € \$8,100 for valve repairs (years 1 and 2);
- € \$1,200 to repair and replace the HD flow control structure (year 5);
- € \$12,500 to repair and upgrade surface water controls damaged during an extreme flood (year 3);
- € \$1,500 to remix the organic substrate in the four HD VFPs (year 5).

Over 6 years the total cost for O & M was \$50,900, which averages to \$8,483/year. Future O & M activities are expected to include major maintenance related to sustaining a viable organic substrate in the VFPs. Eventually, the organic substrates must be removed and replaced. The current cost for organic substrate replacement is estimated at \$45/m³ or approximately \$50,000 per VFP. Based on the performance of the passive systems described in this paper, it will be necessary to replace the substrate approximately every 10–12 years for the Anna system and every 7–9 years for the HD system.

Table 4 Sources of change in net acidity as water flows through VFPs

	Anna VFPs		HD VFPs	
	Change ^a	CaCO ₃ equiv	Change ^b	CaCO ₃ equiv
H ⁺ removal	3.1→ 6.9	47	2.8→ 6.8	76
Al removal	12→ <1	70	36→ <1	197
Fe removal ^c	7 → 3	8	37 → 24	41
Mn removal	8→ 7	2	7 → 7	1
Alkalinity addition	0 → 150	150	0→ 180	180
Total calculated		277		494
Total measured	148→ -108	256	368→ -117	485

^a Flow-weighted in percent of S1 and S2 minus average VFP effluent

^b In percent HD minus average VFP effluent

^c In percent assumed Fe²⁺ and effluent assumed Fe³⁺

Table 5 Average acidity loadings and removal rates for the VFPs

	Size, m ²	Flow, L/min	Acid in,		Acid out, mg/L	Acid removal	
			mg/L	g/m ² /day		mg/L	g/m ² /day
VFP1	3,486	363	148	22.2	-122	267	40.0
VFP2	3,227	269	165	19.8	-104	266	31.9
VFP3	3,029	386	148	27.2	-94	242	44.4
VFP4	3,211	291	165	21.5	-110	275	35.9
VFP5	2,935	216	368	39.0	-121	489	51.8
VFP6	3,799	265	368	37.0	-147	515	51.7
VFP7	3,466	257	368	39.3	-127	495	52.9
VFP8	3,795	265	368	37.0	-115	483	48.6

Table 6 Final average effluent chemistry for the Anna and HD systems during warm (May–October) and cold (November–April) periods; temperatures (°C) are average of daily highs and lows (www.weather.com)

System	Period	Avg temp	n	pH	Alk	Acid	Al	Fe	Mn
Anna	May–October	15.7	9	7.3	151	-106	<1	<1	4
Anna	November–April	-0.1	12	7.3	125	-88	<1	<1	3
HD	May–October	15.7	13	7.4	141	-102	<1	<1	1
HD	November–April	-0.1	15	7.4	151	-124	<1	<1	3

n is number of samples; concentrations in mg/L; alkalinity and acidity as CaCO₃

Cost Evaluation

The costs to design, permit, and construct the treatment systems are shown in Table 7. Design and permitting costs were split evenly between systems, while the construction costs were split in proportion to materials quantities. Total design, permitting and construction costs were approximately \$2.5 million.

Operational costs are incurred by BCWA through its maintenance of the treatment system. These activities are described in the O & M section, include realized routine O&M costs of approximately \$8,483/year and major maintenance activities that occur infrequently but are predictable and can be planned in advance. Currently, the major anticipated maintenance activity is organic substrate

replacement at a cost of \$200,000 per system. Substrate replacement is projected in the current analysis to be required every 8 years of the HD system and every 11 years for the Anna system. This schedule is expected to protect the integrity of the limestone aggregate so that its replacement is not required in a 25 year analysis.

Unit costs calculated based on volume treated and acidity neutralized are shown in Table 8. Both calculations project flows and chemical performance measured over the first 6 years into the future. The unit calculations were conducted over three time periods: 6, 10, and 20 years. The unit costs decrease with time as the large capital investment is spread out over larger flow volumes or CaCO₃ tonnage.

Table 7 Cost to install the Anna S Mine Complex Passive Treatment System in 2003

Capital costs	Anna	HD	Total
Feasibility study	\$15,000	\$15,000	\$30,000
Permitting	\$21,892	\$21,892	\$43,783
Design	\$66,594	\$66,594	\$133,188
Construction management	\$25,875	\$25,875	\$51,750
Construction	\$1,210,054	\$990,045	\$2,200,099
Project management	\$36,523	\$36,523	\$73,046
Total installation	\$1,167,928	\$1,363,938	\$2,531,866

The capital cost includes the solids washing system, which has proven, thus far, ineffective and unnecessary. The total cost of the installed washing system was approximately \$300,000. If this cost is removed, then the unit costs decrease by 5–8%.

Discussion

The Anna S Mine passive treatment complex has provided effective treatment of acid mine drainage since its construction in 2004. The effluent from both treatment systems has always been alkaline, with low concentrations of Fe and Al. The systems have generated, on average,

Table 8 Realized and predicted long-term treatment cost over a 25 year period; costs are not discounted

Item	Anna		HD	
	Freq (year)	Cost	Freq (year)	Cost
Installation	0	\$1,167,928 ^a	0	\$1,363,938 ^a
Routine O & M	1.25	4,242 ^a	1 thru 25	4,242 ^a
Org. substrate replacement	11, 22	\$200,000	8, 16, 24	\$200,000
Unit cost calculations (US \$)				
\$/1,000 L	Year 6	\$0.43	Year 6	\$0.58
\$/1,000 L	Year 10	\$0.25	Year 10	\$0.34
\$/1,000 L	Year 20	\$0.15	Year 20	\$0.19
\$/t net alkalinity (CaC ₃)	Year 6	\$1,779	Year 5	\$1,208
\$/t net alkalinity (CaC ₃)	Year 10	\$1,055	Year 10	\$700
\$/t net alkalinity (CaC ₃)	Year 20	\$618	Year 20	\$403

^a Actual costs

^b Predicted costs

1,037 kg/day of net alkalinity and removed 65 kg/day of decision to bypass untreated AMD around the system was Al, 57 kg/day Fe, and 14 kg/day Mn. Over rst 6 years, thebased on several considerations: (1) protecting the treat- systems generated a total of approximately 2,272 t ofment systems from potentially damaging high ows and net alkalinity and removed 143 t of Al, 125 t of Fe, and loadings, (2) the expectation that excess alkalinity pro- 29 t of Mn. If all of the net alkalinity was generated duced by the system would neutralize a portion of the through calcite dissolution, then approximately 6% of thebypass, and (3) the expectation that acid in ows to the installed limestone has dissolved. receiving stream would receive additional dilution and

Several concerns about the utility and cost-effectivenessnatural neutralization during high ow periods. The pro- of passive treatment for acidic coal mine drainage can bection component has been realized as no damage from evaluated with the available system data. A commorhigh ows occurred in the rst six years. This period concern about passive systems is that they cannot providecluded an extreme ood that damaged surface water reliable treatment in cold weather. The Anna S passivecontrols but did not affect the treatment units. The neu- systems did not display any environmentally signi cantralization component can be assessed by comparing the seasonality in treatment effectiveness. The absence of alkalinity loading of the treatment system ef uents to the cold weather performance decline can be explained byacidity loading of the bypasses (Table 8). Under high ow several factors. First, most of the treatment occurs in theconditions, the Anna system received a maximum of 1,620 VFPs where the water temperature variation is buffered byL/min of ow and discharged about 222 kg/day of the ground temperature. Second, a primary reaction in theet alkalinity. The Anna nal ef uent mixes with bypass VFPs is the dissolution of calcite. Studies of the dissolutionfrom the S1 discharge. The ef uent excess alkalinity on process at 15C indicate that the generation of water with high ow days is able to neutralize 934 L/min of untreated at least 150 mg/L of alkalinity requires 10–15 h of contactS1 bypass. The total neutralized S1 ow, approximately time between the mine water and calcite-containing sub2,327 L/min, is the 97% ow rate for the S1 discharge. The strate (Watzlaf and Hedin1993). The retention time in the Anna system is generating enough net alkalinity to com- VFP limestone underdrains is 60–80 h at average ow andpletely neutralize the S1 discharge 355 days/year. The HD 35–50 h at high ow. Even if temperature variation affects system treats a maximum of about 1,453 L/min of ow and the kinetics of alkalinity generation, there is more thandischarges 235 kg/day of excess alkalinity at high ow. enough retention time to allow the reactions to proceedThis alkalinity can neutralize 443 L/min of untreated near equilibrium under all temperature conditions. bypass. The total neutralized HD ow, approximately

Another concern about passive treatment is the handling,896 L/min, is the 84th percentile ow condition. The HD of variable ow rates. Many treatment systems that func-system is producing enough alkalinity to completely tion well under base ow conditions fail to provide satis- neutralize the HD discharge 307 days per year.

factory treatment under high ow conditions. This problem On very high ow days when the bypasses completely is not speci c to passive treatment. The Anna and HDconsume the systems' alkaline ef uents, the receiving passive systems were constructed with bypasses. Thestream is relied upon to assimilate the residual acidity and

metals. Table 9 shows estimates of the net acidity owing to Wilson Creek during an extreme flow event, after accounting for neutralization by the treatment systems. An estimated 1,200 kg/day of acidity would enter the stream under a 99th percentile flow event. There are no significant AMD in flows to Wilson Creek above the Anna S Mine Complex in flows and the stream is alkaline. A recent base flow measurement of Wilson Creek above the Anna S Mine Complex found 920 kg/day alkalinity (24,591 L/min flow with 26 mg/L alkalinity, measured March 27, 2009). The alkalinity loading would be substantially greater during high flow conditions. The alkaline load of the stream is sufficient to neutralize the in flows of untreated acidic water during high flow events. The adequacy of in-stream neutralization is reinforced by downstream chemical sampling. The mouth of Wilson Run, which averaged pH 5.4 between 1996 and 2001, has had pH greater than 6.3 on every sampling occasion since 2004 (unpublished data collected by the BCWA).

A common concern with vertical flow ponds is their plugging with solids so that mine water does not flow through the substrates as intended by the design. Many passive systems that rely on flow through alkaline substrates have experienced decreased permeability (Rose 2004; Rose and Dietz 2002). The Anna S systems were constructed with features to counter losses in permeability. A flushing system was placed in the top of the limestone layer of each VFP. The VFPs contain water level control structures that allow several feet of head losses to offset each VFP. Neither of these features has proven necessary during the first 6 years of operations. Semi-annual flushing of the VFPs has not produced large quantities of solids. Water elevations in the VFPs have not risen.

The absence of plugging problems is likely related to the raw chemistry and system design. In some VFPs that have displayed permeability problems, the cause has been traced to the accumulation of a thick iron oxide blanket on top of the organic substrate, a result of high iron loading. The Anna and HD VFPs do not receive high iron loadings and do not retain large quantities of Fe. The Fe loading to the Anna and HD systems were only 1–3 g/day Fe and the Fe retention was only 3–7 mg/L Fe. Systems designed for Fe removal are typically loaded at 10–30 g/day Fe and primary treatment units commonly retain more than 50 mg/L Fe (Hedin 2008).

Net Alkalinity Generation

The design of effective VFP systems requires a good estimate of the net alkalinity generation of the technology. The Anna and HD VFPs generated net alkalinity at rates of 32–53 g/m²/day (Table 6). These alkalinity generation rates are consistent with long-term studies of effective VFP

Table 9 High flow treatment effectiveness for the Anna and HD passive treatment systems, 2004–2010

	Anna system	HD system
Flow, average treatment	1,063 L/min	908 L/min
Flow, maximum treatment	1,620 L/min	1,453 L/min
Flow, max, percentile	87%	77%
Influent acidity, average	148 mg/L	368 mg/L
Effluent acid, average	−95 mg/L	−112 mg/L
Effluent acid load at max treatment flow	−222 kg/day	−235 kg/day
System effluent mixes with:	S1 bypass	HD bypass
Effluent neutralization capacity	934 L/min	443 L/min
Total neutralization: flow	2,327 L/min	1,896 L/min
Total neutralization: percentile	97%	84%
Days 100% neutralized	355 days	307 days
Days net acidic mixture	10 days	58 days
99th percentile flow rate	3,407 L/min	3,740 L/min
99th percentile acid load	809 kg/day	1,982 kg/day
Systems' acid neutralization during high flow	567 kg/day	1,004 kg/day
99th percentile net acid load to stream	242 kg/day	977 kg/day

treatment systems. Watzlaf et al. (2000) reported net alkalinity generation rates of 42–62 g/day for vertical flow ponds in southwestern PA. Nairn and Mercer (2000) reported an average net alkalinity generation rate of 51 g/m²/day for a system in southeastern Oklahoma. Rose and Dietz (2002) reviewed the performance of 30 vertical flow systems in Pennsylvania and found systems generating a net alkaline discharge generally had influent acidity loadings less than 40 g/day. Addition analysis of the systems found that VFPs with limestone-amended organic substrates (like the Anna and HD VFPs) were more effective for the treatment of Al-contaminated mine water (Rose 2004). Jage et al. (2001) studied 13 vertical flow systems in Virginia and Pennsylvania and found the net alkalinity generated was statistically related to the retention time and the influent concentrations of Fe and acidity (after adjusting for Mn). The regression equation developed by Jage et al. (2001) calculated net alkalinity generation of 187–207 mg/L CaCO₃ for the Anna VFPs and 283–287 mg/L CaCO₃ for the HD VFPs. These values are 60–80 mg/L lower than the measured alkalinity generation for the Anna VFPs and 200–230 mg/L lower than the measured values for the HD VFPs (Table 5).

An alternative method for predicting net alkalinity generation is based on the expected acidity removal and the concentration of bicarbonate alkalinity in the VFP effluent. Flow of acid mine drainage through an alkaline substrate should raise the pH to 6–7 and remove all dissolved Al.

The acidity neutralization equivalent of this change is calculated from the inuent pH and Al concentrations:

$$\text{Acid neutralization, mg/L CaCO}_3 = \frac{1}{4} 50,000 10^{\text{pH} - 5.6} \text{Al (mg/L)}$$

The discharge concentration of bicarbonate alkalinity is approximated based on empirical results. The concentration of alkalinity discharged by the Anna and HD VFPs was 100–200 mg/L under all ow conditions (Fig. 5a, 6a). Where the AMD is characterized by low pH and Al concentrations greater than 10 mg/L, a first approximation of the expected net acidity removal by a VFP can be calculated from the sum of the acidity loading associated with the H⁺ and Al and the alkalinity loading resulting from the generation of 150 mg/L of alkalinity. This rate can then be used as an acidity removal rate in the sizing the VFP component of the system.

The Anna S passive treatment complex is a primary component of the BCWA's stream restoration program. The success of the program was documented in 2006 when surveys of Babb Creek found water chemistry conditions consistent with its cold water shery designation as well as reproducing trout populations (http://www.epa.gov/nps/Success/state/pa_babb.htm). In 2009, Babb Creek was removed from Pennsylvania's 303(d) list of impaired streams.

Conclusion

The Anna S Mine passive systems have treated acidic metal contaminated mine water for 6 years without substantial problems. The two systems have produced high quality alkaline ef uents during ooding events and through severe winter conditions. The success of the systems is attributable to the conservative treatment system design, decreasing inuent contaminant concentrations, and regular operation and maintenance. The combined systems are the largest and most costly passive treatment complex built to date in Pennsylvania. After 6 years of operation, the systems have generated net alkalinity at a cost of 1,200–\$1,800 per t of CaCO₃. The unit cost of the treatment will decrease with time. With the periodic replacement of the alkaline substrate, the 20 year unit cost is estimated at \$400–600 per t of CaCO₃. This unit cost is highly competitive with alternative lime-based treatment technologies. Doubts about the reliability of passive treatment for acidic waters contaminated with aluminum should be tempered by both these sampling results and the recent removal of the Babb Creek from the Pennsylvania's list of degraded streams.

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