TECHNICAL ARTICLE

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 containing 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 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 4,913 m^3 of organic substrate. During the last 6 years, the systems have treated an average of 1,971 L/min of flow to neutral pH with 135–146 mg/L of alkalinity (as $CaCO_3$), 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/m^2/day as $CaCO_3$. 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 $CaCO_3$) of 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

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1900s. The overburden is highly deficient in neutralizing capability and the drainage produced from the abandoned mines is typically acidic, with pH below 3.5 and elevated concentrations of Al, Mn, and Fe. For at least 50 years, the acid mine drainage (AMD) severely degraded Babb Creek and impaired Pine Creek downstream of the Babb Creek inflow. Native cold water trout fisheries in both streams were mostly eliminated by the AMD.

The Babb Creek Watershed Association (BCWA) was formed in 1990 to promote the restoration of Babb Creek. Between 1990 and 2003, 10 reclamation and water treatment projects were implemented in the watershed. The water treatment actions include an actively managed lime treatment plant and several passive treatment systems. The last major treatment project focused on the Anna S Mine Complex, which discharges approximately 2,800 L min^{-1} of AMD to Wilson Creek, a major tributary of Babb Creek. In 2003/04, passive treatment was installed for three of the four discharges from the Anna S Mine complex. The passive treatment system is the largest passive treatment project to date in Pennsylvania. This paper describes the design and construction of the treatment system and presents the results of the first 6 years of monitoring.

Background

Anna S Mine Complex

The Anna S mine is located 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

bituminous coal seam. Shallow coal along the outcrop was surface mined several times, most recently in the 1980s. The overburden in this area is highly deficient in neutralization potential and is known to produce AMD unless alkaline addition occurs during mining (Reed 1980). No alkaline additions occurred during the mining of the Anna S mine complex.

The mine has produced several large discharges for decades. The southern portion of the complex discharges through a drainage tunnel located beneath the coal crop. This tunnel and its discharge are known as Hunters Drift and will be referred to as 'HD' in this paper. The central portion of the complex discharges through a partially collapsed entry located at the coal crop. 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 backfilled entries referred to as the Mitchell discharges. The Mitchell discharges were not treated by the passive system complex described here.

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 here 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 a 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

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.

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 treatment systems in 2004, flows were measured from pipes discharging AMD into the systems. Pipe flows were measured by the timed-volume method.

Discharge Characteristics and System Design

Table 1 shows the average chemistry for the HD, S1, and S2 discharges measured by the various sampling efforts. Figure 1 shows acidity concentrations for each discharge between 1975 and 2010. Contaminant concentrations for the deep mine discharges increased substantially when the complex was disturbed by surface mining in the early 1980s, but have been decreasing since.

The treatment systems were designed in 2000. The design procedure followed the general guidance of Hedin et al. (1994). The selection of technology was based on chemical conditions, while the sizing was based on targeted loading and predicted contaminant removal rates. All three mine discharges are acidic and require alkalinity generation. Anoxic limestone drains, the simplest passive alkalinity-generating passive technology, were not appropriate because of the presence of aluminum. The selected treatment was the vertical flow pond (VFP) technology that follows after the successive alkalinity producing system (SAPS) concept first described by Kepler and McCleary (1994). The AMD was directed through VFPs, where acidity neutralization and partial metal removal were expected, and then into aerobic ponds and wetlands for aerobic removal of residual metals.

The available property was searched for areas that were lower than the discharges, reasonably flat, and contained deep soils suitable for pond construction without synthetic liners. Two benches were identified that contained appropriate conditions. Two independent treatment systems were designed. Figure 2 shows the layout. The Anna system was located on the upper bench and received the S1 and S2 discharges. The HD system was located on the lower bench and received the HD discharge.

Each system contains four VFPs arranged in parallel followed by aerobic wetlands arranged in series. All three discharges are collected and transferred in buried pipes to the vertical flow ponds. Each discharge collection system connects to a flow control device that limits the amount 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	SO$_4$
Hunters drift (HD)								
1975–1976	Boyer Kantz	12	2.8	348	38	NA	NA	477
1977–1978	USGS, pre-SM[a]	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[a]	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 CaCO$_3$; 'NA' indicates that data were not available

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

water flowing into the transfer pipe. Flows exceeding the limit are bypassed around the treatment systems. Each transfer pipe connects to a distribution structure that creates individual flows that are piped to specific VFPs. The S1 discharge is divided into four flows that are piped to VFP1, VFP2, VFP3, and VFP4. The S2 discharge is divided into two flows that are piped to VFP1 and VFP3. The HD discharge is divided into four flows that are piped to VFP5, VFP6, VFP7, and VFP8. The distribution structures are designed so that the amount of water flowing to each VFP can be modified.

The size of the systems was based on acidity loadings, predicted acidity removal rates, and site constraints. Acidity loadings were calculated as grams per day (g/day) from the product of average influent acidity concentration and the design flow rate. The predicted acidity removal rate was 50 g/m^2/day. The preferred sizing for the VFPs was calculated from the loading and removal rates, as follows:

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

The sizing of the VFPs was affected by site constraints. The design goal for both systems was to treat the 75–90th percentile flows and acidity loadings. The upper bench was large enough to accommodate four VFPs sized for

approximately the 90th percentile loading conditions of the S1 and S2 discharges. The lower bench was not large enough to satisfy these design goals for the HD system. The largest series of VFPs that could be fit on the lower bench were suitable for treatment of the 50th percentile flows and loadings (as assessed in 2000). The design was implemented with a plan to adjust the flow rates to the HD system after installation and determination of treatment effectiveness.

Figure 3 is a typical cross-section of the VFP units. Each contained 1 m of AASHTO #1 limestone aggregate (89% CaCO$_3$) overlain with 0.3 m of alkaline organic substrate. The organic substrate was a mixture of 50% spent mushroom compost, 25% wood chips, and 25% AASHTO #10 limestone (volume percentages). Flow out of each VFP is collected by a pipe underdrain placed at the bottom of the aggregate, and is connected to the effluent pipe through a water level control structure. The water level control box contains removable panels that can be used to manipulate the water elevation within each VFP.

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 VFPs were 3,368 m^2 at the design water surface (0.6 m above the organic substrate) and contained 3,943 metric tons (t) of limestone aggregate overlain with 614 m^3 of organic substrate amended with 493 t of limestone fines.
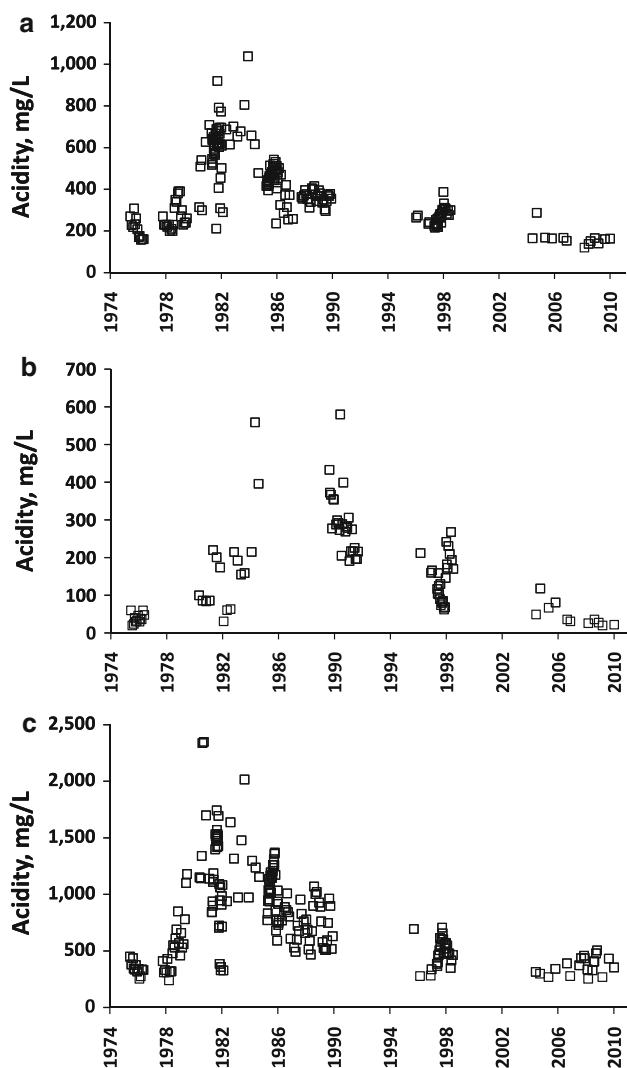
Fig. 1 Acidity concentrations since the 1970's for: **a** the S1 discharge; **b** the S2 discharge; **c** the HD discharge

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, Vs, 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 influents of both systems, the combined VFP

effluents, and the final effluents. Figure 4 shows alkaline and acidic characteristics of the system effluents throughout the 5 years of operation. The final 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 final 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 final 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 (influent acidity minus effluent 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 effluents. The effluents of the VFPs were always net alkaline (Fig. 5). The VFPs removed all of the influent 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 final alkalinity concentrations lower than the VFP effluents.

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 affect on sulfate concentrations (Table 3), 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 changes in each parameter and the calculated CaCO$_3$ equivalent. The sum of the calculated CaCO$_3$ 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
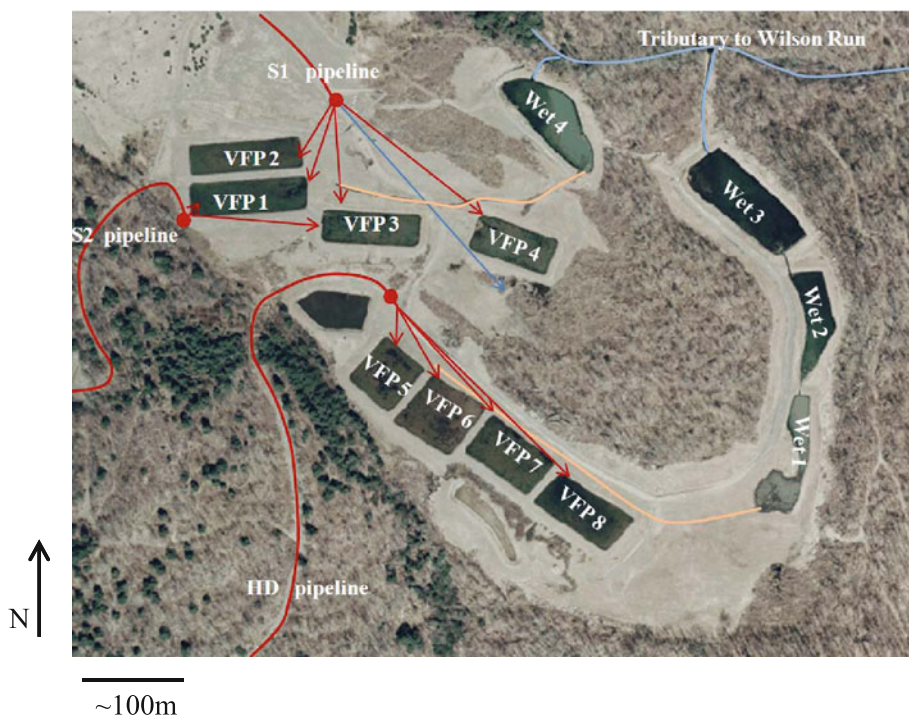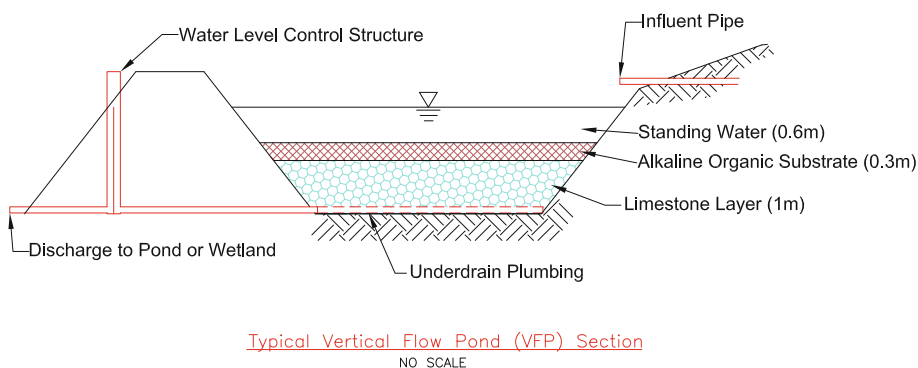

Fig. 3 Typical cross section of the vertical flow ponds

hydrologic loading but a lower acidity loading because the 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; Fig. 1).

The design assumed that the VFPs would generate 50 g/m^2/day of net acidity removal. Over 6 years of treatment, the Anna VFPs generated 31–41 g/m^2/day and the HD VFPs generated 46–52 g/m^2/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), smelled of hydrogen sulfide, and generated foam after aeration. The ditches and wetlands effectively eliminated the color and smell so that the final 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. 4). For the last 4 years, the final 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 final 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 units

	Surface area (m²)	LS layer (t)[a]	Organic substrate	
			Organic, m³	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 passive treatment systems, 2004–2010

	Flow L/min	pH	Alk mg/L CaCO₃	Acid	Fe	Al mg/L	Mn	SO₄
Anna passive system								
S1 inflow	912	3.0	0	165	8	13	9	367
S2 inflow	151	3.7	0	47	1	3	5	150
VFP effluent	NA	6.9	150	−108	3	<1	7	350
Final effluent	NA	7.3	135	−95	<1	<1	4	335
HD passive system								
HD inflow	908	2.8	0	368	37	36	7	552
VFP effluent	NA	6.8	180	−117	24	<1	7	564
Final effluent	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 effluents 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. Effluent 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
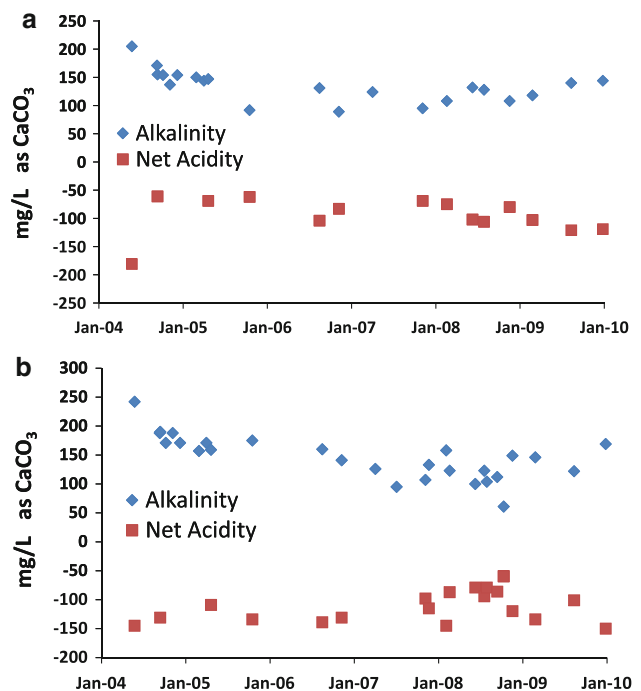

Fig. 4 Concentrations of alkalinity and net acidity at the final discharges of the: **a** Anna and **b** HD systems
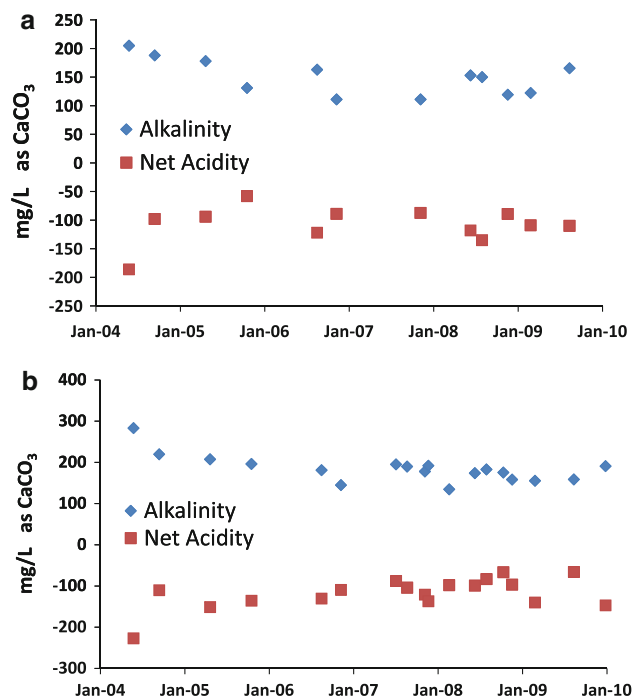

Fig. 5 Concentrations of alkalinity and net acidity for the VFP discharges of the: **a** Anna and **b** HD systems

below 0°C continuously for weeks. Despite major seasonal variation in air temperatures, no seasonable variation in treatment effectiveness was observed. Table 6 shows average final effluent chemical parameters for the two
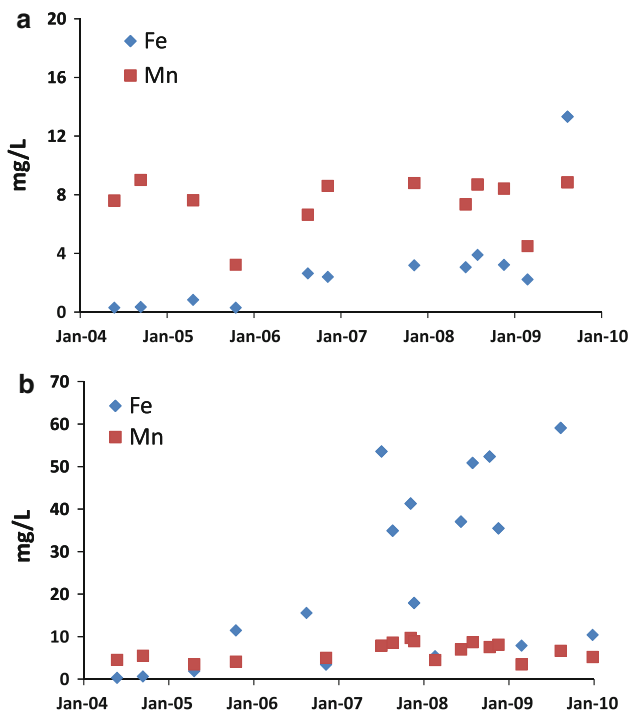
Fig. 6 Concentrations of Fe and Mn for the VFP discharges of the: **a** Anna and **b** HD systems

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, VFP flushing 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/m^3 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 influent of S1 and S2 minus average VFP effluent

[b] Influent HD minus average VFP effluent

[c] Influent assumed Fe^{3+} and effluent assumed Fe^{2+}

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 CaCO$_3$

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. The 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, 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

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

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 CaCO$_3$ tonnage.

The capital cost includes the solids flushing system, which has proven, thus far, ineffective and unnecessary. The total cost of the installed flushing 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 final 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[b]	8, 16, 24	$200,000[b]
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
$/t net alkalinity (CaCO$_3$)	Year 6	$1,779	Year 5	$1,208
$/t net alkalinity (CaCO$_3$)	Year 10	$1,055	Year 10	$700
$/t net alkalinity (CaCO$_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 Al, 57 kg/day Fe, and 14 kg/day Mn. Over first 6 years, the systems generated a total of approximately 2,272 t of net alkalinity and removed 143 t of Al, 125 t of Fe, and 29 t of Mn. If all of the net alkalinity was generated through calcite dissolution, then approximately 6% of the installed limestone has dissolved.

Several concerns about the utility and cost-effectiveness of passive treatment for acidic coal mine drainage can be evaluated with the available system data. A common concern about passive systems is that they cannot provide reliable treatment in cold weather. The Anna S passive systems did not display any environmentally significant seasonality in treatment effectiveness. The absence of a cold weather performance decline can be explained by several factors. First, most of the treatment occurs in the VFPs where the water temperature variation is buffered by the ground temperature. Second, a primary reaction in the VFPs is the dissolution of calcite. Studies of the dissolution process at 15°C indicate that the generation of water with at least 150 mg/L of alkalinity requires 10–15 h of contact time between the mine water and calcite-containing substrate (Watzlaf and Hedin 1993). The retention time in the VFP limestone underdrains is 60–80 h at average flow and 35–50 h at high flow. Even if temperature variation affects the kinetics of alkalinity generation, there is more than enough retention time to allow the reactions to proceed near equilibrium under all temperature conditions.

Another concern about passive treatment is the handling of variable flow rates. Many treatment systems that function well under base flow conditions fail to provide satisfactory treatment under high flow conditions. This problem is not specific to passive treatment. The Anna and HD passive systems were constructed with bypasses. The

decision to bypass untreated AMD around the system was based on several considerations: (1) protecting the treatment systems from potentially damaging high flows and loadings, (2) the expectation that excess alkalinity produced by the system would neutralize a portion of the bypass, and (3) the expectation that acid inflows to the receiving stream would receive additional dilution and natural neutralization during high flow periods. The protection component has been realized as no damage from high flows occurred in the first six years. This period included an extreme flood that damaged surface water controls but did not affect the treatment units. The neutralization component can be assessed by comparing the alkalinity loading of the treatment system effluents to the acidity loading of the bypasses (Table 9). Under high flow conditions, the Anna system received a maximum of 1,620 L/min of flow and discharged about 222 kg/day of net alkalinity. The Anna final effluent mixes with bypass from the S1 discharge. The effluent excess alkalinity on high flow days is able to neutralize 934 L/min of untreated S1 bypass. The total neutralized S1 flow, approximately 2,327 L/min, is the 97% flow rate for the S1 discharge. The Anna system is generating enough net alkalinity to completely neutralize the S1 discharge 355 days/year. The HD system treats a maximum of about 1,453 L/min of flow and discharges 235 kg/day of excess alkalinity at high flow. This alkalinity can neutralize 443 L/min of untreated bypass. The total neutralized HD flow, approximately 1,896 L/min, is the 84th percentile flow condition. The HD system is producing enough alkalinity to completely neutralize the HD discharge 307 days per year.

On very high flow days when the bypasses completely consume the systems' alkaline effluents, the receiving stream is relied upon to assimilate the residual acidity and

metals. Table 9 shows estimates of the net acidity flowing 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 inflows to Wilson Creek above the Anna S Mine Complex inflows 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 inflows 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 in 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/m^2/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/m^2/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/m^2/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/m^2/day for vertical flow ponds in southwestern PA. Nairn and Mercer (2000) reported an average net alkalinity generation rate of 51 g/m^2/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/m^2/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 (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 CaCO$_3$ for the Anna VFPs and 283–287 mg/L CaCO$_3$ 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 influent pH and Al concentrations:

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

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 flow conditions (Figs. 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 fishery 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 effluents during flooding events and through severe winter conditions. The success of the systems is attributable to the conservative treatment system design, decreasing influent 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–$1,800 per t of CaCO$_3$. 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 $400–600 per t of CaCO$_3$. 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.

References

American Public Health Association (APHA) (1999) Standard methods for the examination of water and wastewater. In: Clesceri LS, Greenberg AE, Eaton AD (eds), 20th Edit, American Public Health Assoc, American Water Works Assoc, and the Water Environment Federation, Washington, DC, USA

Boyer Kantz and Associates (1976) Operation Scarlift, Babb Creek mine drainage abatement project. PA Department of Environmental Resources, Scarlift Report, 125 pp, http://amrclearinghouse.org/Sub/SCARLIFTReports/

Hedin RS (2006) The use of measured and calculated acidities to improve the quality of mine drainage data sets. Mine Water Environ 25:146–152

Hedin RS (2008) Iron removal by a passive system treating alkaline coal mine drainage. Mine Water Environ 27:200–209

Hedin RS, Nairn RW, Kleinmann RLP (1994) Passive treatment of coal mine drainage. USBM IC 9389, US Department of the Interior, Washington DC, USA, 35 pp

Jage CR, Zipper CE, Noble R (2001) Factors affecting alkalinity generation by successive alkalinity-producing systems: regression analysis. J Env Qual 30:1015–1022

Kepler DA, McCleary EC (1994) Successive alkalinity producing systems (SAPS) for the treatment of acidic mine drainage. Proceeding, International Land reclamation and mine drainage conference and the 3rd international conference on the abatement of acidic drainage, vol 1. Pittsburgh, PA, USBM SP 06A-94, US Department of the Interior, Washington DC, USA, pp 195–204

Nairn RW, Mercer MN (2000) Alkalinity generation and metals retention in a successive alkalinity producing system. Mine Water Environ 19:124–133

Reed LA (1980) Effects of strip mining the abandoned deep Anna S mine on the hydrology of Babb Creek, Tioga County, Pennsylvania. USGS WRI 80-53, US Department of the Interior, Washington DC, USA, 41 pp

Rose AW (2004) Vertical flow systems—effects of time and acidity relations. Proceeding annual meeting of the american sociecty of mining and reclamation and the 25th West Virginia Surface Mine Drainage Task Force, Morgantown WV, USA, pp 1595–1616

Rose AW, Dietz JM (2002) Case studies of passive treatment systems: vertical flow systems. In: Proceeding annual meeting of the american sociecty of mining and reclamation, Lexington KY, USA, pp 776–797

Watzlaf GR, Hedin RS (1993) A method for predicting the alkalinity generated by anoxic limestone drains. Proceeding 13th Annual West Virginia surface mine drainage task force symposium, West Virginia Univ, Morgantown, WV, USA

Watzlaf GR, Schroeder KT, Kairies C (2000) Long-term performance of alkalinity-producing passive systems for the treatment of mine drainage. In: Daniels WL, Richardson SG (eds) Proceeding 2000 annual meeting of the american sicotey for surface mining and reclamation, Tampa, FL, USA, pp 262–274

Weaver KR, Lagnese KM, Hedin RS (2004) Technology and design advances in passive treatment system flushing. Proceeding annual meeting of the american sicotey of mining and reclamation and the 25th West Virginia Surface Mine Drainage Task Force, Morgantown WV, USA, pp 1974–1989

Younger PL, Banwart SA, Hedin RS (2002) Mine water: hydrology, pollution, remediation. Kluwer Academic Publishers, Dordrecht, 442 pp