Effective Passive Treatment of Coal Mine Drainage[1]

Robert Hedin, Ted Weaver, Neil Wolfe, George Watzlaf

Hedin Environmental, 195 Castle Shannon Blvd, Pittsburgh, PA 15228, USA, bhedin@hedinenv.com

Abstract Contaminated mine drainage on abandoned coal mine sites can be treated by passive or active treatment techniques. Passive treatment is less costly than active treatment, but its reliability is often questioned. This paper presents a simple design approach that has been used to design passive treatment systems in Pennsylvania for the past 20 years. Four systems that demonstrate commonly utilized passive technologies are described and long-term data are presented. The systems have provided highly reliable and effective treatment for 3-18 years. The data demonstrate that properly designed, constructed, and maintained passive treatment systems are a highly cost-effective solution for contaminated mine discharges on AML sites.

Introduction

Contaminated coal mine drainage can be treated by active and passive techniques. Active treatment typically includes chemicals, mechanical equipment, and labor associated with operations and sludge management. Passive treatment utilizes gravity, natural materials and processes, minor labor demands, and can produce a marketable sludge. Chemical treatment systems have smaller footprints and require less land area than passive systems. However, the cost of chemical treatment when calculated over a 20-40 year period is typically 2-10 times higher than passive alternatives. One commonly espoused justification for this expense is that chemical treatment is more reliable than passive treatment. The purpose of this paper is to examine the reliability of established passive treatment systems and provide a current calculation of the cost of passive techniques over long time frame.

Background

The systems presented here were designed by Hedin Environmental (HE), a small consulting firm that specializes in passive mine water treatment. Since 1994 HE has designed 47 passive treatment systems that have been installed largely in Pennsylvania. The design of the systems follows guidance presented by US Bureau of Mines Information Circular 9389, Passive Treatment of Coal Mine Drainage (Hedin, Nairn, and Kleinmann 1994). This publication presented design and performance data for existing systems and provided a decision tree for the design of passive systems. A modified version of the decision tree is shown in Figure 1. Other decision trees have been developed that include additional technologies. This tree includes non-proprietary technologies that have been found by HE to be capable of reliably producing a final system effluent with neutral pH and low metal concentrations.

The decision tree recognizes five passive treatment technologies which are described below.

Oxidation and/or Settling Pond Ponds are intended to retain water long enough to achieve oxidation or solids settling goals. Oxidation is required for waters containing ferrous iron or dissolved organics. Settling is required for waters containing suspended ferric and aluminum hydroxide solids. The ponds are sized based on retention time or metal loading. Ponds are an important tool in the treatment of alkaline Fe-contaminated waters, the discharge from vertical flow ponds, and the discharge from a drainable limestone beds.

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Constructed Wetland Constructed wetlands are intended to polish effluents before discharge. The wetlands included here are aerobic and contain shallow water depths. Wetlands are commonly positioned after settling ponds where they remove residual suspended solids that are difficult to remove in ponds. Wetlands are also used for Mn removal.

Anoxic Limestone Drain An anoxic limestone drain (ALD) is a buried bed of limestone that adds alkalinity to flow-through acidic water through carbonate dissolution. The “drain” name is an artifact of early systems that were designed similar to french drains. A better terminology would be anoxic limestone *bed*. ALDs are not appropriate for waters containing Al or ferric iron (Fe^{3+}) because these metals will form solids within the limestone aggregate, decrease its permeability, and eventually plug the system. For anoxic waters contained with ferrous iron or manganese, the ALD is the most effective and least costly method available for treating acidity (Ziemkiewicz, Skousen and Simmons 2003). The design of ALDs is described in Watzlaf and Hedin (1993) and Hedin, Watlaf and Nairn (1994).

Oxic Limestone Bed An oxic limestone bed (OLB) is open to the atmosphere. Acidity is neutralized through carbonate dissolution. OLBs were originally developed for pH adjustment and Mn removal. Mn occurs through the formation of dense Mn solids and, under most conditions, plugging of the aggregate does not occur for at least ten years. Mn removal in oxic limestone beds appears to be faster than in wetlands. A recent modification is the *drainable* limestone bed (DLB) where the oxic limestone bed is drained empty regularly (weekly) in order to maintain the aggregate porosity and permeability. This approach has proved effective for treating AMD containing Al and ferric iron without the plugging problems that occur with anoxic limestone drains are exposed to these metals. More information on the DLB is available at Wolfe, Hedin, and Weaver (2010).

Vertical Flow Pond A vertical flow pond (VFP) is a pond that contains a layer of limestone aggregate overlain by an alkaline organic substrate overlain by water. AMD enters on the surface and flows vertically down through the organic substrate, where pH adjustment and Al removal occurs, and down through the limestone where alkalinity generation occurs. An under drain collects the water and discharges. The VFP was developed for acidic waters containing Al and ferric iron. While these metals form solids that will eventually foul the substrates, the large surface area provided by the vertical flow approach provides years of performance before the substrates need rehabilitation. Because of the organic matter, the discharge from a VFP typically contains dissolved organics and reduced sulfur compounds. A settling pond is required to remove these contaminants.

The decision tree (Figure 1) is a series of chemical assessments that provide technological recommendations. The first determination is whether the discharge is alkaline or acidic. Net alkaline discharges do not require alkalinity generation and the typical problems are ferrous iron and manganese. These contaminants are removed with oxidation/settling ponds, constructed wetlands, and oxic limestone beds. If the discharge is net acidic, alkalinity generation is required and several choices are available. If the discharge is anoxic and does not contain Al or ferric iron, an ALD is suitable. If the discharge is not appropriate for an ALD, then either a VFP or DLB is suitable. The criteria distinguishing these two choices are not clear at this time (to the author). DLBs have not been tested on AMD with high Fe concentrations, so the VFP approach may be more suitable for acidic water with more than 20 mg/L Fe. If Mn removal is required, the DLB should be considered. DLB systems have a smaller footprint, but require more maintenance than VFP systems.

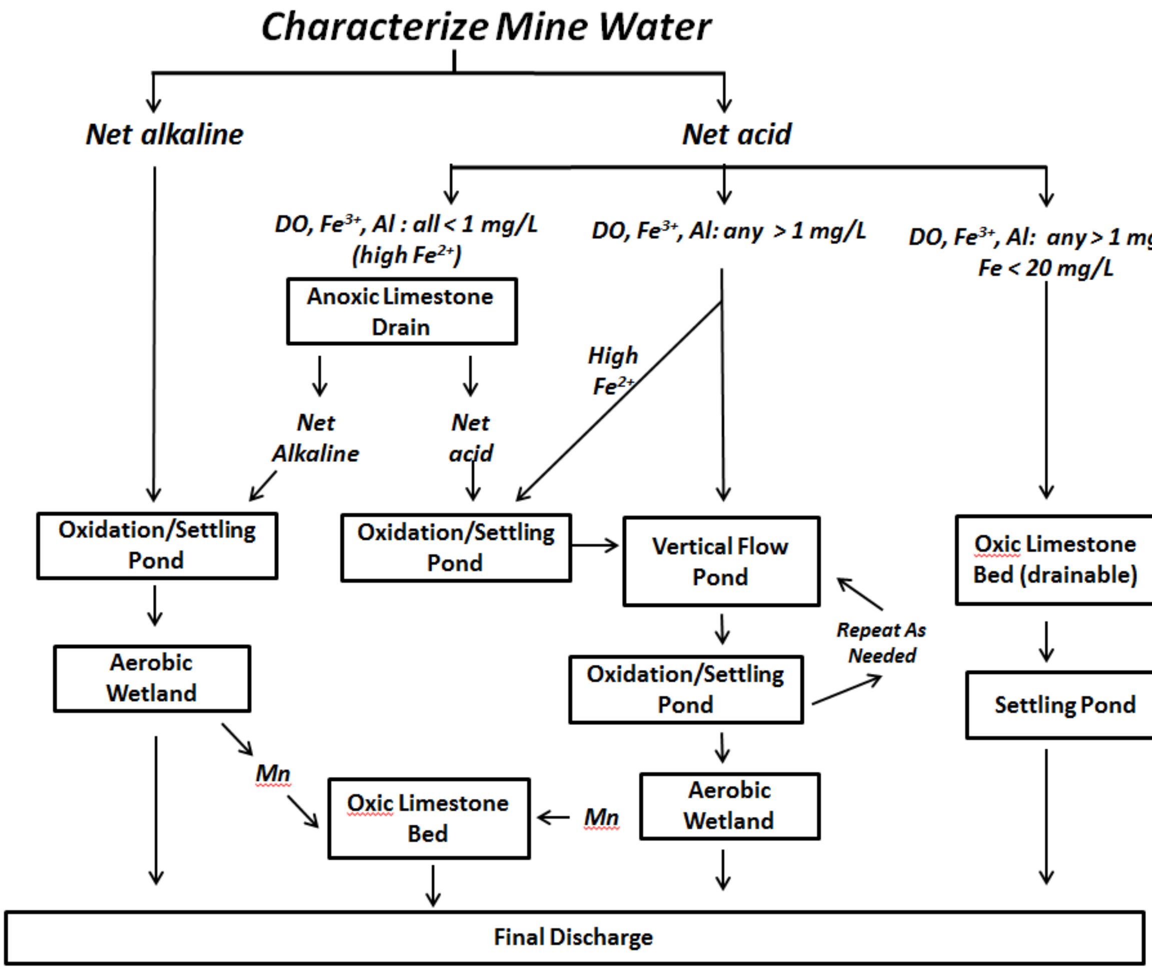

***Figure 1**. Decision tree for the design of passive treatment systems.*
Key: DO, dissolved oxygen; Fe^{3+}, ferric iron; Fe^{2+}, ferrous iron; Al, aluminum; Mn, manganese

Results: Case Studies

Four examples of the effectiveness of the core technologies are presented. The Marchand system is an aerobic system that has been treating a net alkaline Fe-contaminated deep mine discharge since 2007 with oxidation/settling ponds and a constructed aerobic wetland. The SR-114D system has treated an acidic Fe-contaminated discharge since 1995 with an anoxic limestone drain. The Anna S system has treated acidic discharges contaminated with Al, Fe^{3+}, and Mn since 2004 with vertical flow ponds and aerobic wetlands. The Scootac system has treated an acidic discharge contaminated with Al and Mn since 2010 with a drainable limestone bed and settling pond.

Marchand Passive System: Ponds and Constructed Wetland

The Marchand Mine passive treatment system is shown in Figure 2. It is located at 40° 14’ 04.81” N; 79° 45’ 55.63 W. The system was installed in 2006 to treat a large Fe-contaminated discharge from an underground mine in the Pittsburgh coal seam that was active in the first half of the 20th century. The mine is flooded and has discharged since the 1950’s. The passive treatment system was constructed in 2006 for $1.3 million, which included design, permitting, and construction. Funding was provided by a grant from the Pennsylvania Growing Greener Program to the Sewickley Creek Watershed Association. The system was constructed on an 18 acre AML property obtained by Sewickley Creek Watershed Association for a nominal cost. The discharge originally flowed directly to the stream in a channel at an elevation that did not allow passive treatment. The discharge was raised 5 feet which provided the gravity flow needed to support a passive design. The system consists of six serially-connected ponds (total surface area of 230,000 ft^2) followed by a single 320,000 ft^2 constructed wetland. The ponds were constructed in compacted clay (no organic substrate) and have retained an open-water environment. The wetland was constructed with the best available soil (obtained onsite) and planted with a mix of aquatic plant species. The system is described in more detail in Hedin (2008).

Table 1 shows the average flow and chemistry of the influent, effluent of the final pond (F) and effluent of the wetland (system final effluent). The influent flow rate ranged between 1,268 and 2,481 gpm and has averaged 1,876 gpm. The mine water is alkaline and contains approximately 72 mg/L Fe. The system effluent has contained an average 1 mg/L. Figure 3 shows influent and effluent Fe concentrations between 2007 and 2013. Of 96 measurements of Fe in the final effluent, only 4 were higher than 3 mg/L and the highest measurement was 6.0 mg/L. The treatment system was effective year round. A significant cold weather decline in the removal of Fe was not evident.

The system’s operation and maintenance involves routine inspections/monitoring and sludge management. The system produces approximately 350 ton/yr of iron solids. Problems with iron scaling of pipes that connect the ponds were corrected by replacing three of the most problematic pipes with open troughs in 2012. Iron solids in the first three ponds were removed in 2012 and collected in geotubes which are visible in Figure 2 adjacent to Pond A. The cost of the sludge removal was $120,000. About $40,000 of this cost was infrastructure that will be used in future sludge removal efforts. It is anticipated that solids management will cost ~$160,000 every 8 years or, on an annualized basis, $20,000/year. Routine sampling and inspections costs are about $5,000/yr. The total annual cost, $25,000/yr, has a 20 year present value (5%) of $311,000. The total 20 year cost of the system (installation and operation) is $1.6 million.

The solids produced by the passive treatment are ~90% pure iron oxide (FeOOH) which is being processed for eventual sale (Hedin 2012). If the iron solids can be successfully sold then the long-term costs will be largely eliminated, decreasing the total 20 year present value cost to $1.3 million (system construction).

Table 1 *Average conditions at the Marchand Mine passive treatment system, Jan 2007 – May 2013. TSS is total suspended solids.*

	Flow	**pH**	**Alk**	**Acid**	**Fe^{tot}**	**Fe^{dis}**	**Mn^{tot}**	**Al^{tot}**	**SO$_4^{tot}$**	**TSS**
	gpm	**s.u.**	**mg/L**	**CaCO$_3$**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
Influent	1,876	6.30	335	-189	72.4	66.8	1.2	< 0.1	1,036	25
Pond F out	na	7.10	230	-196	12.4	1.4	1.1	< 0.1	1,117	16
Effluent	na	7.76	216	-188	1.0	0.1	0.5	< 0.1	1,160	<6

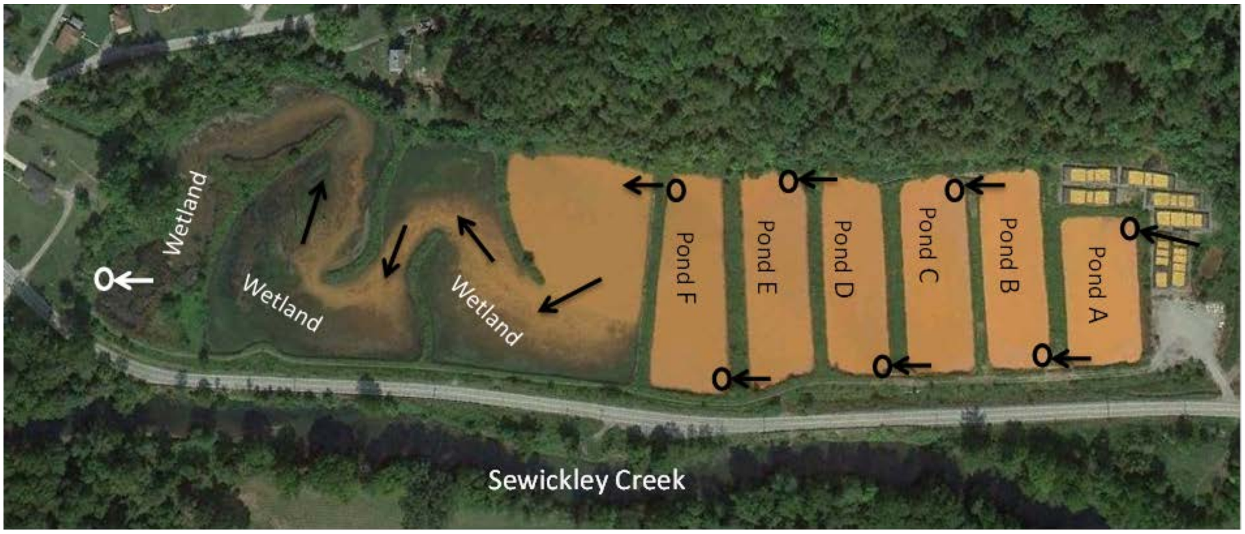

Figure 2 *Marchand passive treatment system on August 29, 2012. Arrows show flow paths. Circles are sampling points.*

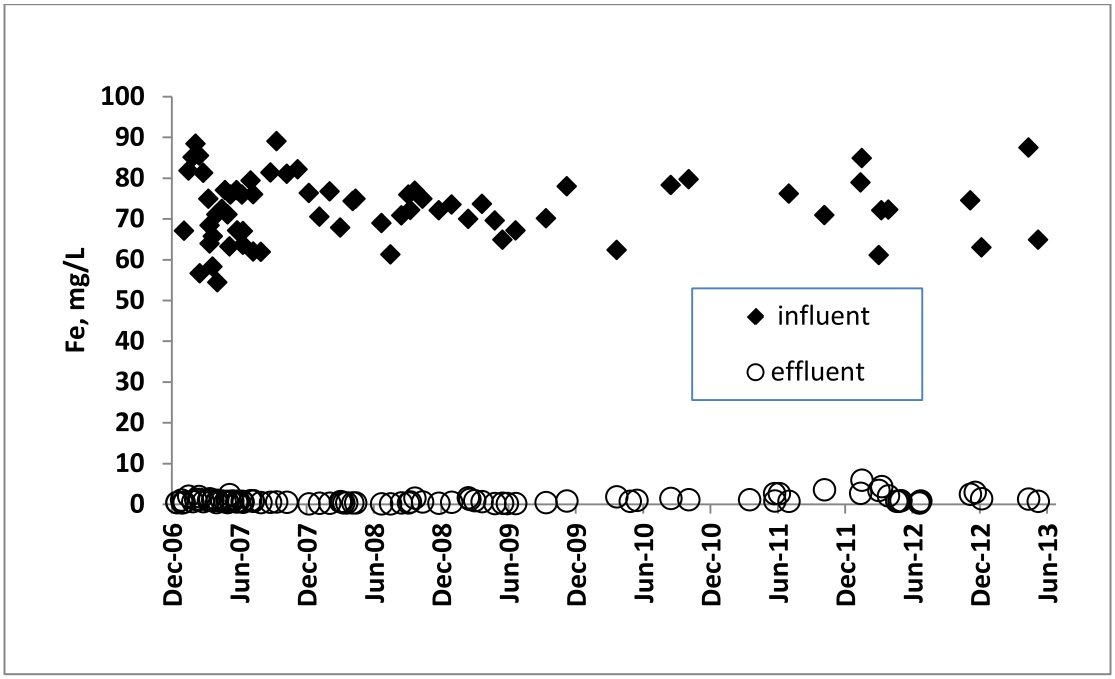

Figure 3. *Concentrations of Fe at system influent and effluent.*

SR-114D: Anoxic Limestone Drain

The SR4114D treatment system was installed in 1995 as part of a bond forfeiture project. The system location is 41^o 05’ 43.30 N, 79^o 49’ 36.05 W. The site contains an abandoned above drainage underground mine in the Brookville coal seam that was sealed in the 1970’s through an AML project. The primary discharge in 1995 was an artesian flow from an abandoned well located below the sealed mine. It was postulated that the flooded mine was flowing into an underlying aquifer and the well provided a conduit for the aquifer to discharge to the surface. Many artesian flows of acid mine drainage in northwestern Pennsylvania are a consequence of a similar interaction of AML and abandoned wells (Hedin, Stafford, and Weaver 2005).

The original AMD had pH 6 and contained 52 mg/L alkalinity but had a net acidity of 58 mg/L due to the presence of 43 mg/L Fe and 1 mg/L Mn. (Al was less than 1 mg/L). The passive system included an anoxic limestone drain (ALD) followed by a settling pond, three constructed wetlands, and a very large pre-existing natural wetland. During the excavation of the ALD an abandoned gas well was intercepted which produced AMD. Both discharges were collected and piped into a single 1,300 ton ALD. The cost of the ALD construction was approximately $30,000 in 1995 and today would be approximately $60,000. When the system was constructed in 1995, the ALD was the believed to be the largest one in northern Appalachia. The ALD is the focus of this discussion.

Over the last 18 years the ALD’s discharge has been sampled 54 times for alkalinity (Figure 4) and 45 times for total Fe (Figure 5). Flow, which is measured at a weir at the final effluent, has been measured 33 times. The ALD’s discharge flow rate has averaged 114 gpm and has not changed substantially during the last 18 years. The Fe concentration of the ALD discharge has averaged 36 mg/L and has not changed over the last 18 years (figure 5). The ALD initially produced 150-200 mg/L alkalinity, but has recently decreased to about 100 mg/L. To maintain a net alkaline discharge, the alkalinity should be at least 65 mg/L. This condition is being achieved.

Alkalinity is generated in ALDs through the dissolution of calcite. Studies of existing ALDs have concluded that retention of 10-15 hours is needed to obtain the maximum amount of alkalinity from the limestone (Watzlaf and Hedin 1993; Hedin, Watzlaf, and Nairn 1994). The retention time for the SR-114D ALD at the time it was constructed was about 11 hours. Since 1996, the ALD has lost about 224 tons of limestone (17% of its original tonnage) and the retention time at average flow has decreased to 9 hours. This decay in retention time in the limestone bed is likely responsible (partially) for the decrease in alkalinity production.

The ALD has not required any maintenance over the last 18 years. This is a typical result for properly designed and constructed ALDs. The ALD will require major maintenance when the limestone dissolution advances to a point where the effluent is no longer net alkaline or the hydrologic conductivity of the limestone is compromised by stone loss. It is anticipated that the ALD’s eventual rehabilitation that will involve its excavation, repairs to influent and effluent piping, and replacement of about 500 tons of limestone. The cost for this activity is estimated at $20,000-30,000. Assuming a $30,000 cost every 20 years, $1,000/yr routine O&M, and an initial construction cost of $60,000 (2013 dollars), then the 20 year present value cost for the ALD is approximately $95,000. This calculation only considers the ALD and does not account for the system’s pond and wetlands.

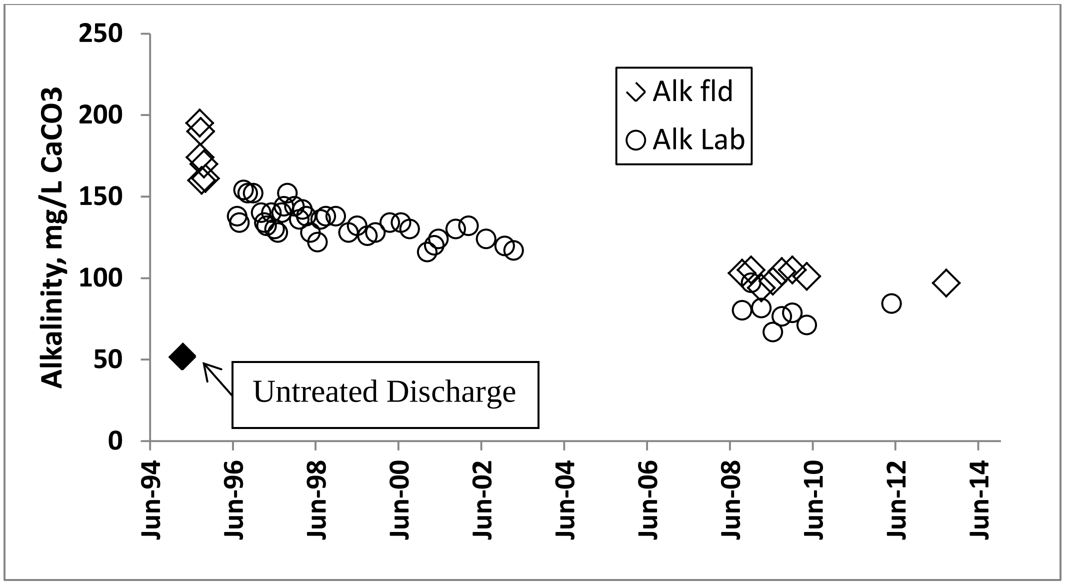

Figure 4. *Concentrations of alkalinity at the SR-114D ALD effluent. Diamonds are field measurements and circles are laboratory measurements.*

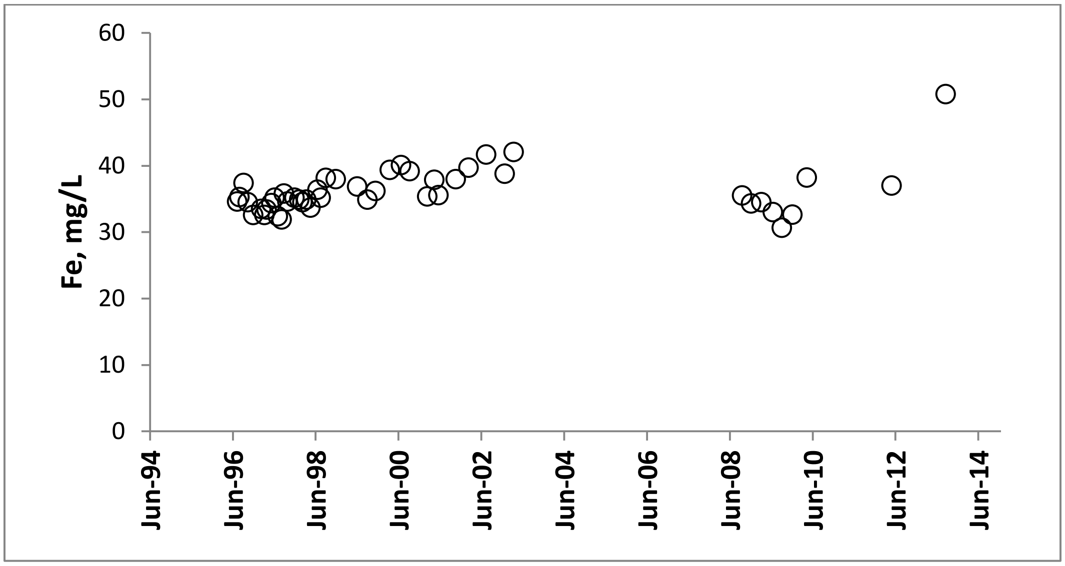

Figure 5. *Concentrations of Fe (total) at the SR-114D ALD effluent.*

Anna S Passive Treatment Complex: Vertical Flow Ponds and Wetlands

The Anna S Mine passive treatment complex is shown in Figure 6. Its location is 41^o 37' 17.21 N, 77^o 18' 07.94 W. Two independent systems treat three discharges from an abandoned underground mine in the Bloss coal seam. The only suitable treatment area was located 1,200 – 3,200 ft from the discharges, so they were each collected and piped (8" HDPE) to the treatment area. The AMD is low pH and contains elevated Al, Fe, and Mn. Both systems treat the acidic water with four parallel vertical flow ponds followed by constructed wetlands. Each system contains a flow distribution structure that splits the AMD and pipes it independently to the VFPs. This design allows one VFP to be shut down for maintenance while flow to the other VFPs continues and treatment is not disrupted. The effluents from each VFP are then combined and directed into the wetlands for polishing and final discharge. The VFPs and wetlands were constructed in on-site soils without synthetic liners. More information about the sytem's design is available in Hedin et al. (2010).

The VFPs were designed similarly. Each contains 3 ft of limestone aggregate overlain with 1 foot of alkaline organic substrate which is overlain with 1-2 ft of water. The VFPs range in size from 31,500 ft^2 – 40,800 ft^2 and contain (individually) 3,100 – 4,200 tons of limestone aggregate and 700-900 CY of organic substrate. These are large VFPs and the passive treatment complex is the largest passive treatment project implemented in Pennsylvania to date. The project was funded with $2.2 million from the Pennsylvania Growing Greener program and $300,000 from the Office of Surface Mining. The systems were installed in 2003/04 and have been operating continuously since 2004. The Babb Creek Watershed Association received the funds, managed the construction, and has conducted O&M operations over the last 10 years.

The systems have provided good reliable treatment of the AMD. Table 2 shows the average chemistry of the influents, the VFP effluents, and the final effluents. All three AMD inflows are acidic, but the chemistry of the HD discharge is particularly severe. The VFPs raise the pH, add alkalinity, remove most of the Al, a portion of the Fe, and have little effect on Mn. Flow through the wetlands removes residual Fe and a portion of the Mn. Figures 7 and 8 show concentrations of alkalinity at the final effluents. Every effluent sample has been strongly net alkaline.

The Babb Creek Watershed Association inspects the system monthly and conducts maintenance as needed. Routine O&M costs about $5,000/yr. In 2010 the organic substrates in the several VFPs in each system were inspected. The substrate in the VFPs in the Anna system was found to be ~70% viable which was considered a positive finding. The substrate in the VFPs in the HD system was found to be 25-50% viable. Because of this finding, the organic substrate in the four HD VFPs was rehabilitated in 2012/13. Approximately 9 inches of new alkaline organic substrate was added to each VFP. The cost of this major maintenance activity was $200,000. A similar activity is expected to be needed for the Anna VFPs in the next three years. It is expected that the organic substrates will need to be replaced every 8 years for the HD VFPs and every 12 years for the Anna VFPs. The total annualized cost for routine O&M and organic substrate rehabilitation is $45,000/yr which has a 20 year present value cost of $560,000. The total cost of the system (2004 construction plus PV of future O&M) is $3.1 million.

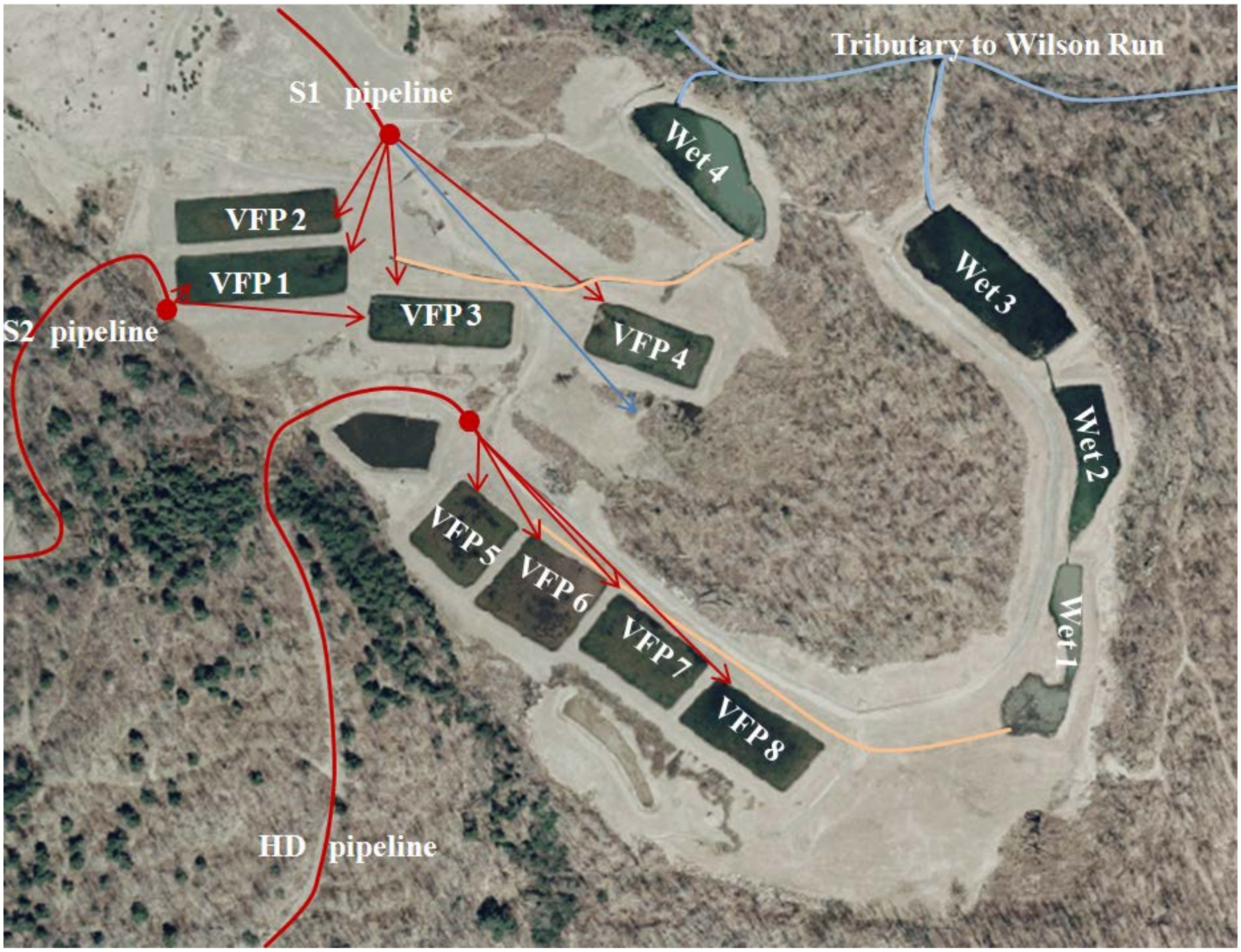

Figure 6. *Layout of the Anna S Mine Passive Treatment Complex. The Anna system includes the S1 and S2 discharge, VFPs 1 -4, and Wetland 4. The Hunters Drift system includes the HD discharge, VFPs 5-8, and wetlands 1-3.*

Table 2. *Average influent and effluent chemistry for the Anna S systems, 2004 – 2013.*

	Flow	**pH**	**Alk**	**Acid**	**Fe**	**Al**	**Mn**	**Sulfate**
	gpm	**s.u.**	**mg/L**	**$CaCO_3$**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
Anna S1 influent	223	3.2	0	152	7	12	8	359
Anna S2 influent	36	3.8	0	37	<1	2	6	144
VFPs effluent	na	6.9	143	-104	4	<1	7	328
Anna final effluent	na	7.4	131	-97	<1	<1	4	321
HD influent	253	2.8	0	344	34	33	7	536
VFPs effluent	na	6.8	174	-118	16	<1	5	505
HD final effluent	na	7.4	140	-108	<1	<1	2	496

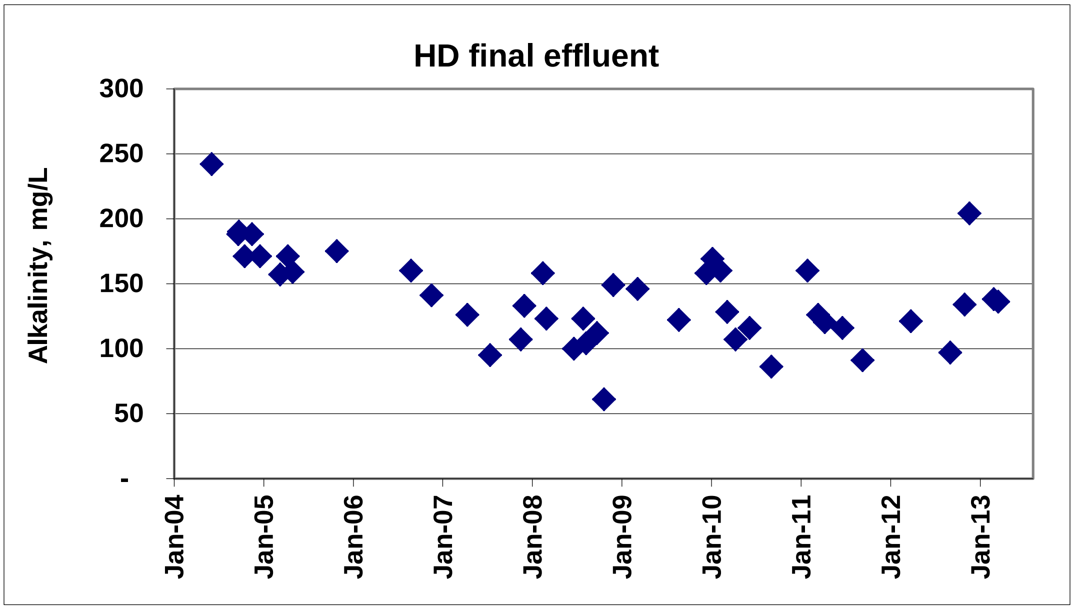

Figure 7. *Alkalinity concentration at the final effluent of Hunters Drift System*

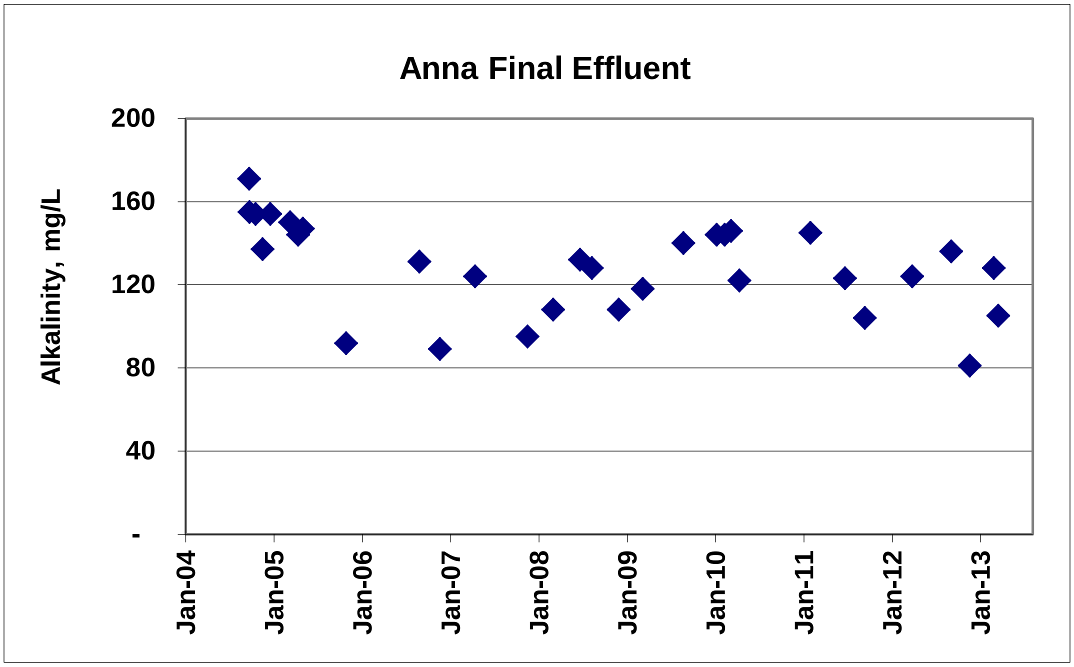

Figure 8*. Alkalinity concentration at the final effluent of Anna S1 & S2 System*

Tangascootac #1 Passive System: Drainable Limestone Bed

The Tangascootac#1 passive system was initially installed in 2000 to treat an acidic mine spoil discharge contaminated with Al and Mn. Its location is 41^{o} 08' 37.36 N, 77^{o} 38' 45.09W. The system did not perform well because of design and construction problems. In 2010 the system was rehabilitated and a 1,000 ton drainable limestone bed was installed. The cost of the rehabilitation was $110,000, of which about $80,000 was for the DLB. The project was funded by a Pennsylvania Growing Greener grant to the Clinton County Conservation District. The District managed the project and is responsible for system O&M.

The input to the system is a previously installed French drain that collects seepage from the mine spoil. A flow control structure directs up to 100 gpm of flow to the drainable limestone bed, which discharges to a settling pond. The drainable limestone bed is open to the atmosphere. Water enters on the surface and is collected at the bottom of the bed with an underdrain that discharges through a water level control structure that maintains the water level in the DLB about 6 inches below the surface of the limestone. The water level control structure is equipped with a gate valve in the bottom panel that automatically opens once/week and drains the limestone bed. The gate valve's operation is controlled by a computer that is powered with a solar panel (Agri Drain Smart Drainage System). By regularly draining the bed empty, the porosity of the limestone aggregate is maintained and the limestone is able to treat Al-contaminated AMD years longer than is the case without this activity (Wolfe and Hedin 2010).

Table 3 shows the average influent and effluent chemistry of the DLB during its first 3 years of operation. Figure 9 shows flow rates, influent acidity and effluent acidity. The flow rate has varied between 17 and 100 gpm. The system has generated a strongly net alkaline discharge on every sampling occasion. The system has lowered Al to less than 0.5 mg/L. The surprising aspect of the DLB's performance has been the removal of Mn (Figure 10). Since March 2011, the effluent Mn concentrations have been less than 0.5 mg/L.

The DLB is drained once/week. The drainage water flows to the final settling pond which has effectively retains the solids. The pond effluent has averaged less than 0.5 mg/L Al.

The draining of the limestone bed does not remove all of the metal solids and eventually the limestone aggregate will become fouled with solids and require rehabilitation. The cost to clean limestone in a DLB designed to facilitate the activity is about $5/ton. This compares to a cost of approximately $30/ton to replace the limestone. It is anticipated that the Scootac bed will need to be cleaned every 3-5 years at a cost of $6,000 or an annualized cost of $1,500/yr. Routine monitoring and O&M costs are about $1,500/yr. The total annualized O&M cost is $3,000/yr which has a 20 year present value of $40,000. The total 20 year cost of the DLB (construction plus operation) is $120,000.

Table 3*. Average influent and effluent chemistry for the Scootac DLB, Nov 2010 – Dec 2012*

	Flow	**pH**	**Alk**	**Acid**	**Fe**	**Al**	**Mn**	**SO_4**
	gpm			**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
Influent	na	4.0	0	91	0.2	11.6	26.9	975
DLB Effluent	48	7.3	215	-188	0.1	0.1	1.4	1017

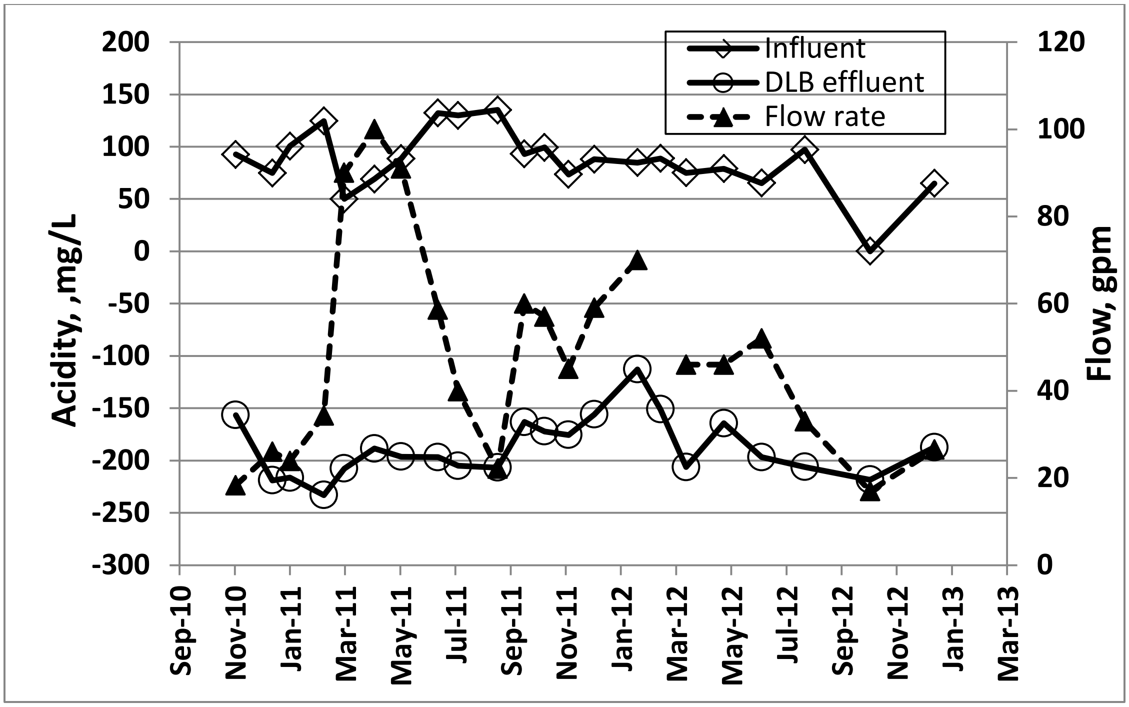

Figure 9. *Influent and effluent acidity and flow rates at the Scootac #1 DLB*

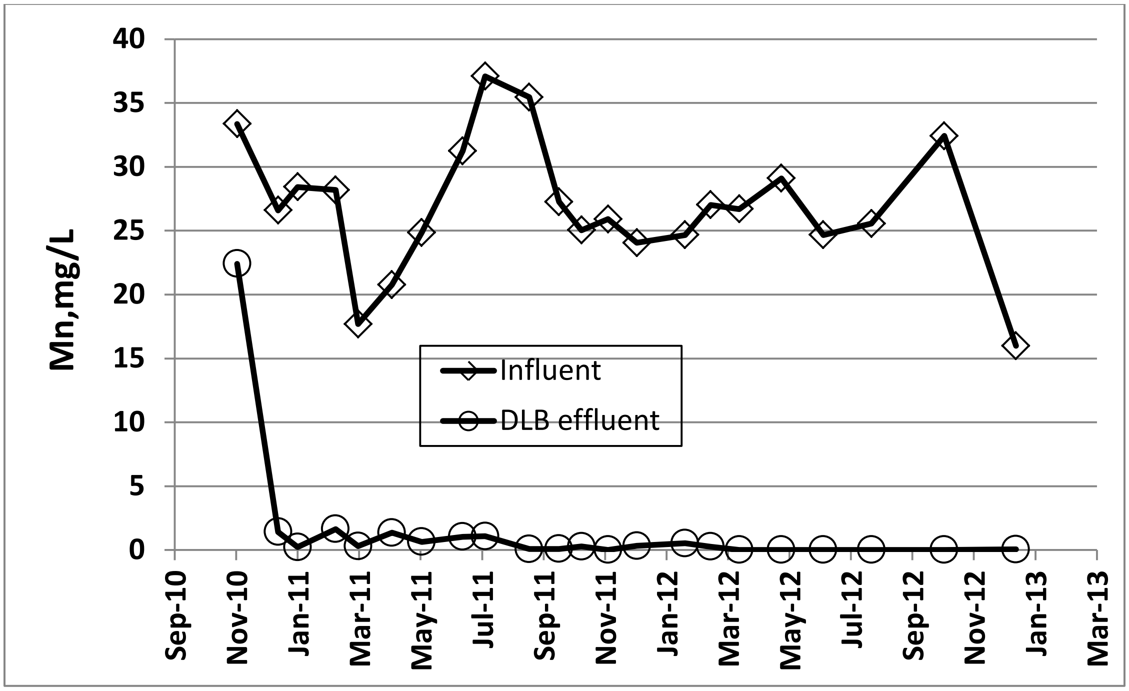

Figure 10. *Influent and effluent concentrations of Mn at the Scootac #1 DLB*

Conclusions

Passive treatment is an option for the treatment of contaminated drainage at abandoned mine sites. The design of an effective passive treatment system requires understanding of the mine water chemistry and the capabilities of available technologies. Most mine drainage problems encountered on AML sites in the Appalachian coal fields can be treated with simple passive technologies. This paper has presented a method for selecting technologies and provided examples of long-term treatment effectives for four passive systems. Properly designed, constructed, and maintained passive systems provide highly reliable treatment at a fraction the cost of active alternatives.

Acknowledgements

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