CASE STUDY: "THE JENNINGS SYSTEM" – OVER A DECADE OF SUCCESSFUL PASSIVE TREATMENT[1]

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Abstract. Treatment of drainage from an underground coal mine, abandoned for over 65 years, has been a focus of the Jennings Environmental Education Center (a Pennsylvania State Park) since failure of a mine seal in 1984. Early prototypes of environmentally-friendly technologies or passive treatment components have been installed and monitored since 1989. As Jennings is dedicated to environmental education at various interest levels for the general public and for students of all ages, water monitoring to demonstrate the performance of the system has been imperative. In 1997, a Vertical Flow Pond (VFP) with treatment media consisting of 272 metric tons (300 short tons) of spent mushroom compost mixed with 345 metric tons (380 short tons) [9.52 mm x 1.180 mm (3/8"x16 mesh); >90% $CaCO_3$] of limestone aggregate, a step-down (Bioswale) wetland, and an aerobic wetland/settling pond were installed to treat the acidic, metal-laden, raw water which averages 76 Lpm (20 gpm), 3.0 pH, 270 mg/L acidity, 40 mg/L total iron, 15 mg/L total manganese, and 15 mg/L total aluminum. At the time of installation, the predicted optimum life of the VFP treatment media was 7 to 10 years with exhaustion in about 14 years. After over 12 years, however, the system continues to provide successful treatment with limited maintenance. The primary maintenance item has been two, approximately two-day, "stirring" events to address permeability of the treatment media. As a design schematic and analyses from over 200 water monitoring events (depending upon the component), conducted by numerous professionals, students, and volunteers, are publically available online at www.datashed.org, the passive system provides a valuable template for future designs and improvements. The final effluent of the system can be characterized as typically net alkaline with total iron, manganese, and aluminum concentrations of about 1 mg/L or less.

Additional Key Words: AMD, Vertical Flow Pond, Operation and Maintenance,

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[1] Paper was presented at the 2010 National Meeting of the American Society of Mining and Reclamation, Pittsburgh, PA ***Bridging Reclamation, Science and the Community*** June 5 - 11, 2010. R.I. Barnhisel (Ed.) Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

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Proceedings America Society of Mining and Reclamation, 2010 pp 154-169

DOI: 10.21000/JASMR10010154

http://dx.doi.org/10.21000/JASMR10010154

Introduction

Prior to successful implementation of a passive treatment system, drainage from an abandoned coal mine created a 1.2-ha (3-acre) "kill zone" (area with poor to no vegetation) and degraded Big Run, a local tributary to Slippery Rock Creek (Ohio River Basin), at the 121-ha (300-acre) Jennings Environmental Education Center (Jennings), a Pennsylvania Department of Conservation and Natural Resources State Park in Brady Township, Butler County. Through public-private partnership efforts, environmentally-friendly technologies have been and are being implemented to address the impact to both the land and water resources from historical mining activities. Hands-on education programs are provided to increase public awareness not only of these technologies, but also of the contributions by government agencies, mining companies, environmental professionals, academic institutions, and volunteers. Through the on-going interest and commitment by these various organizations and individuals, monitoring is available to demonstrate the effectiveness of these restoration efforts. The focus of this paper is the development, installation, maintenance, and long-term performance of passive treatment components that were installed in 1997.

Background

Mining and Early Reclamation Efforts

Located in the Appalachian Plateau Province in the high-volatile bituminous Middle Kittanning coalbed (Pennsylvanian Allegheny Gp.; Kittanning Fm.), the Brydon Mine (a.k.a., Foltz Hill Mine) was a small, room-and-pillar operation which was active between 1935 and 1944. A coal preparation plant with coal refuse covering ~ 3.2-ha (~8 acres) was located downgradient of the two drift entries. Workings extended under about 28-ha (70 acres) and were to the rise of the coal. Four major efforts to eliminate or to provide long-term treatment of the degraded drainage have been conducted during the last 40 years.

In the 1960s, the Commonwealth of Pennsylvania through the Operation Scarlift Program funded an investigation of abandoned mine drainage (AMD) problems in the Slippery Rock Creek Watershed (Gwin, 1970). As a result, coal refuse was removed, the site was revegetated, and mine seals were installed to eliminate degraded drainage from the two drift entries of the Brydon Mine. In 1984, however, the seals failed and the AMD flowed about ~400 meters (1200 feet) through Jennings prior to entering Big Run. Further land reclamation was also needed as vegetation had not been successfully established in the area of coal refuse removal.

Initial AMD Treatment Effort

In 1987, the Pennsylvania Department of Environmental Resources (PADER) Bureau of Abandoned Mine Reclamation (BAMR) constructed a sediment pond, two aerobic wetland cells, and a polishing pond to operate in series. BAMR monitored what is now known as the "lower wetland system" between 1989 and 1991. Even though monitoring demonstrated significant improvement in water quality, the desired effluent quality was not achieved.

Table 1. Lower Wetland System: Comparison of Influent and Effluent Characteristics (average values)

Point	Flow Rate	pH	Alkalinity	Acidity	T. Fe	T. Mn	T. Al	Sulfates
Influent	129 (34)	2.90	0	258	22	6	19	516
Effluent (WL4)	NA	3.33	0	154	15	6	14	519

Flow rate - L/min (gpm); pH - standard units; alkalinity & acidity - mg/L $CaCO_3$; total metal values - mg/L [iron (TFe), manganese (TMn), aluminum (TAl)]; sulfates - mg/L; not available (NA) (Ref: Dietz et al, 1994)

Figure 1. Aerial view (winter 1992); "lower wetland system" (upper right corner); drift entries (center left); area for passive treatment system installation and revegetation (center). (photo by PADEP, Knox District Mining Office)

Public-Private Partnership Efforts in AMD Treatment

In 1992, with the formation of the Jennings Water Quality Improvement Coalition (JWQIC) and support from the PADER Knox District Mining Office, U. S. Bureau of Mines, Quality Aggregates, Inc., Amerikohl Mining Inc., Slippery Rock University, and volunteers from CDS Associates, Inc., an anoxic limestone drain (ALD) was installed upgradient of the "lower wetland system" and east of a major local public road (PA State Route 8). The ALD contained a total of 362 metric tons (400 short tons) of limestone aggregate (AASHTO #1, >90% $CaCO_3$) in six cells 0.9 meters deep x 0.9 meters wide (3 feet deep x 3 feet wide) with a combined length of 175 meters (575 feet). The effluent, which was conveyed to the original watercourse, mixed with minor sources of untreated AMD prior to entering the "lower wetland system". Monitoring was conducted of the ALD influent and effluent as shown in Table 2. Field measurements of the "lower wetland system" effluent (WL4) were not recorded during the operation of the ALD.

Table 2. Anoxic Limestone Drain: Comparison of Influent and Effluent Characteristics (average values)

Point	Flow Rate	pH	Alkalinity	Acidity	T. Fe	T. Mn	T. Al	Sulfates
Influent	na	3.3	0	NR	81	9	21	691
Effluent	92 (24)	6.3	177	NR	62	9	<1	680

Flow rate-L/min (gpm); pH-standard units; alkalinity & acidity-mg/L $CaCO_3$; total metal values-mg/L [iron (TFe), manganese (TMn), aluminum (TAl)]; sulfates-mg/L; not available (NA); not reported (NR) (Ref: Hedin et al, 1994)

After six months of operation, "plugging" problems (loss of permeability) developed in the ALD and partially-treated mine drainage began to seep from the second cell. The flow rate of the seep increased over the next 3 months from 5% to 95% of the total.

In 1994, to aid in the development of a new technology, a pilot-scale project to evaluate the effectiveness of utilizing spent mushroom compost as the treatment media in a Vertical Flow Pond was installed with the assistance of Sunbeam Coal Corp. and monitored by the JWQIC. This project also evaluated utilizing a piping system embedded in limestone aggregate (underdrain) beneath the media to collect and to convey the treated water. Although initial results were very promising, within 13 months the effluent became acidic.

In 1995, the JWQIC proposed to construct a passive treatment system based on innovative vertical flow technology. The proposal was funded by the PADER Bureau of Watershed

Conservation under the US Environmental Protection Agency Section 319 Program. This system was placed on-line in 1997 and is the focus of the following discussion.

Vertical Flow Pond

A passive treatment system consisting of a Vertical Flow Pond (VFP) followed by a Bioswale and aerobic wetland/settling pond (WL/SP) was constructed in 1997. The raw water influent piping to the VFP was connected to an existing collection system installed ca. 1992 by the U. S. Bureau of Mines, CDS Associates, Inc., and volunteers. Geotextile was used as a pond liner. The underdrain was constructed using 5.08-cm (2-inch), solid, PVC headers with 1.90-cm (¾-inch) perforated PVC laterals spaced at 1.82-meter (6-foot) intervals. The underdrain piping was then embedded in AASHTO #57 river gravel (non-reactive) 0.3-meter (1-foot) in thickness. The headers are connected to a 10.2-cm (4-inch) corrugated plastic outlet pipe. Woven, permeable, geotextile was installed over the bedding stone of the underdrain to separate the treatment media. The treatment media consists of 272 metric tons (300 short tons) of spent

Figure 2. Grove City College and Slippery Rock University students assisting Charles D. Cooper, PE, PLS (CDS Assoc., Inc.) with the installation of the VFP underdrain (1997).

mushroom compost amended with 345 metric tons (380 short tons) of 9.52 mm x 1.18 mm (3/8" x 16 mesh), >90% $CaCO_3$, limestone. The limestone and spent mushroom compost were mixed and placed with a hydraulic excavator. Girl Scouts, homeschooled students, and Grove City College and Slippery Rock University students constructed the underdrain and assisted with mixing and placement of the treatment media.

Passive Treatment Monitoring and Performance

Water monitoring of the untreated abandoned mine discharge (Raw), Vertical Flow Pond effluent (VFP) and Wetland/Settling Pond effluent (WL/SP) has been conducted at various frequencies from September 1997 to date. Monitoring has been conducted by representatives from federal and state government agencies, colleges and universities, environmental professionals, and volunteers. While there has been substantial monitoring of this passive system by many different groups not all of the data collected were available at the time of writing this paper. Efforts are currently underway to acquire, organize, and upload the data to Datashed (www.datashed.org) in order to provide a more complete record at a publically-accessible location. Volunteer monitoring generally consists of field measurements for pH, flow rate, total iron, and alkalinity (water quality parameters measured by LaMotte field kits).

A summary of the water quality data for the Raw, VFP, WL/SP, and WL4 are presented in Table 3 including average, minimum, median, and maximum values. Wetland 4 (WL4) is the final pond of the original "lower wetland system" and is the final effluent of the entire treatment system, prior to entering Big Run. (See Fig. 3.) Only data from six recent comprehensive sampling events in 2008 and 2009 were available for WL4, post-construction of the VFP and associated components. As can be seen, the system is very effective at treating the acidic abandoned mine discharge that contains relatively high concentrations of Fe, Al, and Mn.

A study of vertical flow-type ponds conducted by the U.S. Department of Energy, National Environmental Technology Laboratory concluded that the Jennings VFP produced the greatest change in net acidity than any other similar pond that was included in that study (Watzlaf, 2004 and Watzlaf, 2000). Even after nearly 13 years of operation, the Jennings VFP effluent is still typically net-alkaline with over 140 mg/L of alkalinity and contains essentially no dissolved aluminum. The total iron concentration has been decreased by about half of that observed in the raw AMD. The remaining iron is predominantly retained in the WL/SP that follows. The

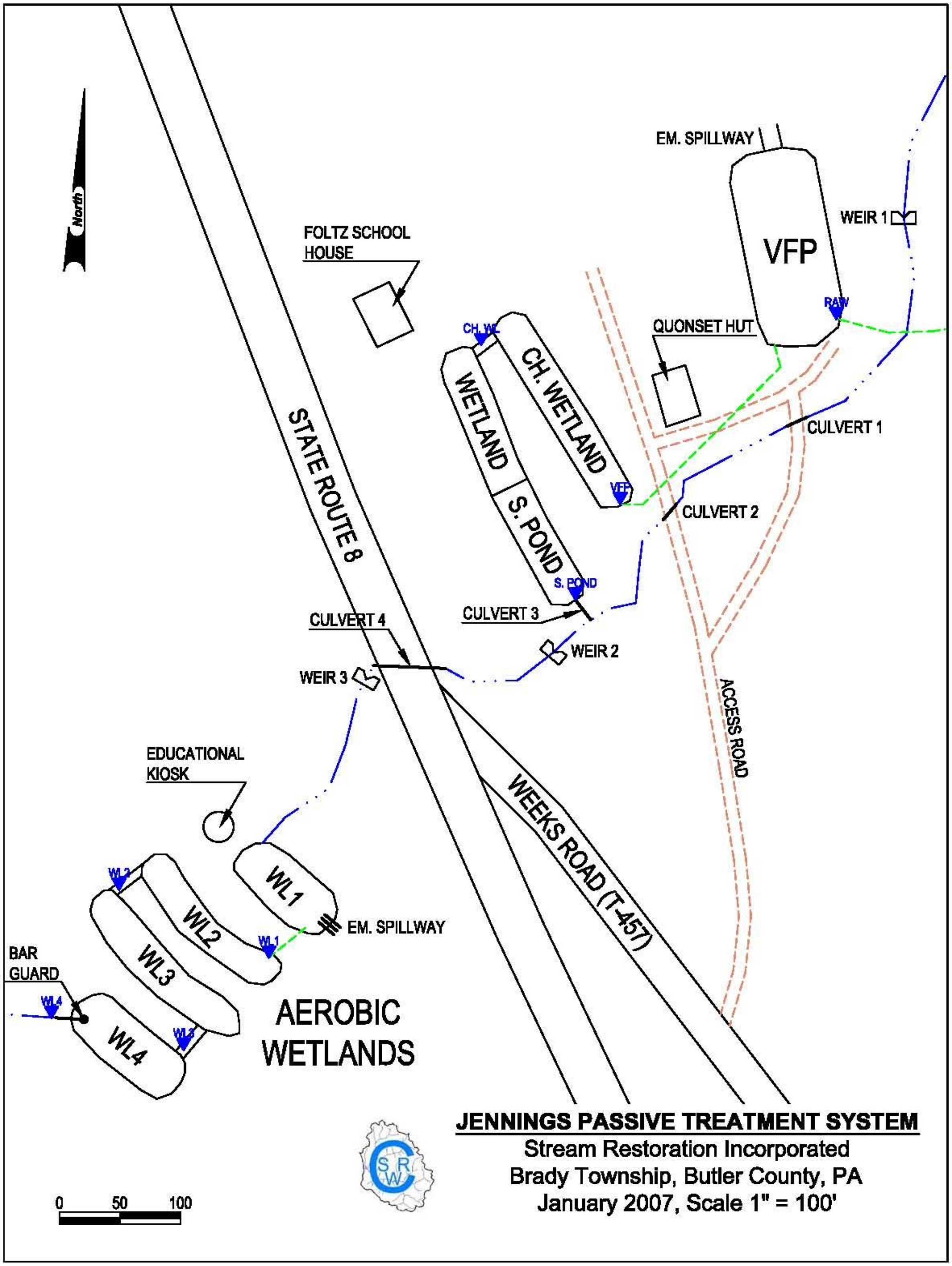

Figure 3. Schematic of Jennings Passive Treatment System
(Note: Aerobic Wetlands, a.k.a. "Lower Wetland System"; former ALD in area below VFP)

effluent of WL/SP mixes with a small portion of untreated mine water that intentionally by-passes the VFP for demonstration/educational purposes. The effluent and untreated drainage mix together with the combined flow rate measurable by an in-stream weir. Additional degraded mine drainage and surface run-off in response to precipitation events are intercepted and conveyed through a culvert underlying the public road (PA State Route 8) to the "lower wetland system". With the excess alkalinity generated by the VFP, sufficient buffering capacity is available to ameliorate the impact of the additional degraded seepage and the final effluent at WL4 is, therefore, typically net-alkaline with very low concentrations of Fe, Mn, and Al.

Table 3. Comparison of Influent & Effluent Characteristics Values: *average* min/median/max

Point	Flow	Lab pH	Field Alk	Lab Alk	Acidity	T. Fe	T. Mn	T. Al
Raw (n=86-139)	*76* 23/68/185	*3.0* 2.2/3.2/4.8	*0* 0/0/0	*0* 0/0/0	*267* 40/272/459	*37* 1/31/86	*14* 1/14/23	*15* 1/14/32
VFP (n=86-304)	*79* 15/79/185	*6.4* 5.4/6.6/8.0	*170* 84/172/256	*106* 22/98/232	*-52* -250/-41/39	*13* 1/9/56	*13* 1/14/24	*2* 0/1/20
WL/SP (n=7-172)	*79* 15/79/185	*6.4* 5.3/7.0/7.7	*81* 16/82/140	*86* 43/82/121	*-77* -25/-69/116	*2* <1/1/9	*10* 1/12/16	*<1* <1/<1/2
WL4 (n=6)	*83* 53/57/151	*6.2* 5.7/6.4/6.7	*27* 10/27/37	*23* 4/23/36	*-9* -21/-13/14	*<1* <1/<1/<1	*2* 1/1/4	*<1* <1/<1/1

*Number of samples (n) varies among sample points & individual parameters; flow (Lpm); pH - std. unit); acidity, alkalinity, and total metals - mg/L; R**aw** (untreated AMD and VFP influent; **VFP** (effluent of VFP and Bioswale influent conveyed to WL/SP; **WL/SP** (effluent of WL/SP, enters watercourse conveyed to WL1, to WL2, to WL3, to WL4; **WL4** (Final effluent enters watercourse conveyed to Big Run)*

A series of graphs have been included to provide a visual overview of the effectiveness of the system. Figure 4 compares hot acidity values in the raw untreated mine water with the effluent of the VFP over time. Note that except for a few occasions, the VFP has almost always produced net-alkaline water. Figure 5 compares total iron values in the raw water with the effluent of the VFP and of the WL/SP over time. Typically, the WL/SP has less than 5 mg/L of total iron, which is assumed to be primarily particulates. Figure 6 compares total Al values in the raw water with the effluent of the VFP and of the WL/SP over time. Even when the total Al value for the VFP effluent is greater than 1 mg/L, the majority of the Al is assumed to be in the form of particulates, as the pH is generally greater than 6. (Note "gaps" in monitoring data especially for the WL/SP effluent as shown in Fig. 5 & 6.)

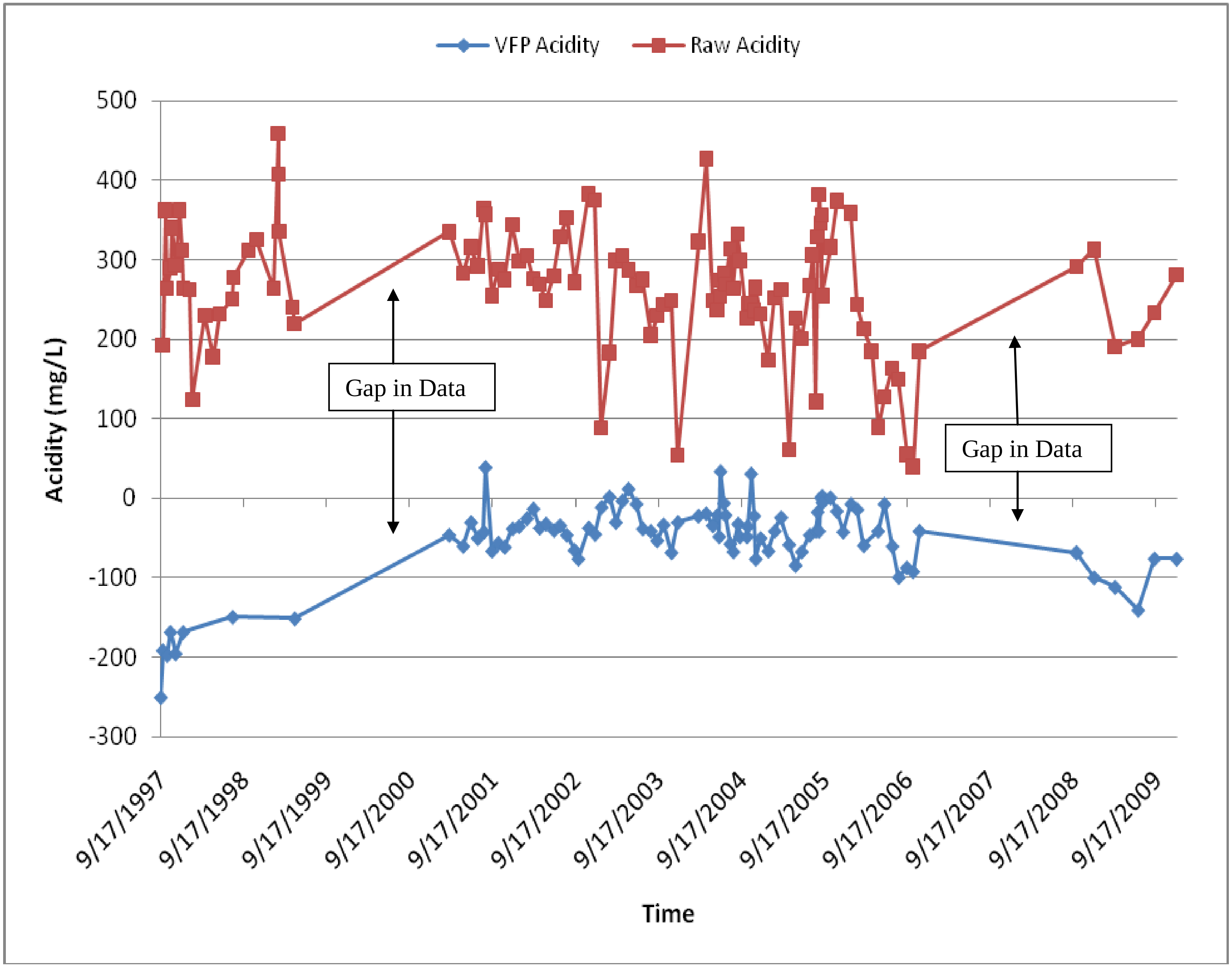

Figure 4. Comparison of Acidity: Raw (VFP Influent) and VFP (Effluent)

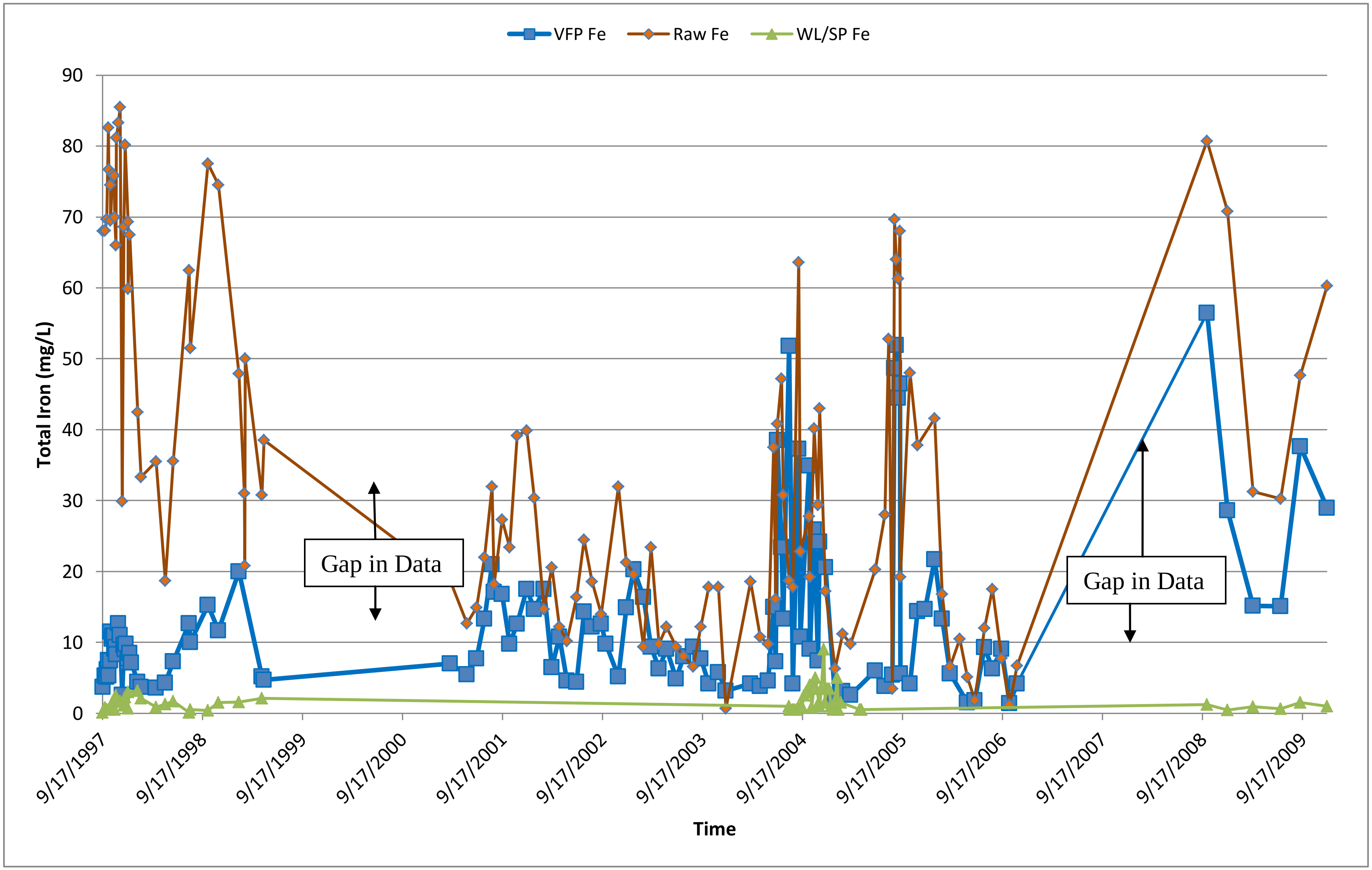

Figure 5. Comparison of Total Iron: Raw (VFP Influent), VFP (Effluent), WL/SP (Effluent)
(Note: VFP effluent is the influent to the Bioswale which conveys the flow to the WL/SP.)

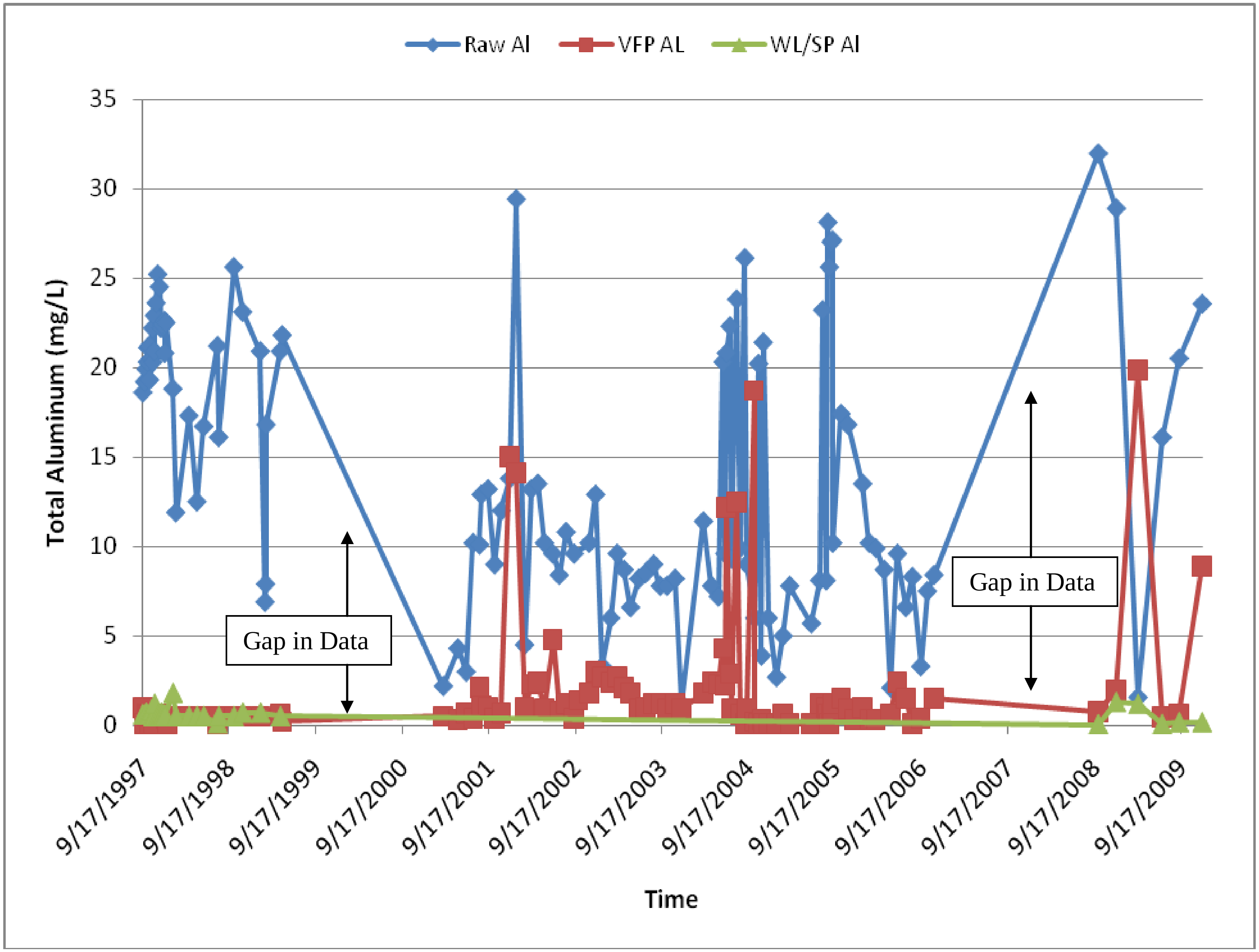

Figure 6. Comparison of Total Aluminum: Raw (VFP Influent), VFP (Effluent), WL/SP (Effluent)

System Maintenance

The Jennings VFP was one of the first of its kind. As stated in the final report submitted to the PADEP, based on the average alkalinity production and changes in calcium concentration within the first 600 days of operation, theoretically the limestone aggregate would be exhausted after about 14 years and the entire substrate (treatment media) would probably need to be replaced within 7-10 years (Jennings Water Quality Improvement Coalition, 1999). While unsure of specific maintenance needs, the report also stated that the accumulation of iron and Al solids overlying and within the treatment media was expected to cause maintenance issues.

As expected, some maintenance activities have been necessary to continue effective treatment. The only substantive activity, however, relating to system performance has been "stirring" the treatment media within the VFP. As described previously, the VFP treatment media consists of a mixture of spent mushroom compost and limestone aggregate. After several years of operation, a decrease in the VFP effluent flow rate was noted, resulting in a discharge from the emergency spillway. A variety of hypotheses were considered including plugging of the underdrain and/or effluent piping, clogging of the permeable geotextile that separated the treatment media from the bedding stone of the underdrain, a decrease in permeability (hydraulic conductivity) due to the accumulation of iron solids overlying the treatment media, etc. As the VFP effluent continued to be net alkaline and as documentation of long-term treatment effectiveness without maintenance was of interest, there was hesitation to try to rehabilitate the system.

In 2002, however, a very limited maintenance/investigation effort was conducted by volunteers in order to attempt to determine the root cause of the problem. First, the 10.2-cm (4-inch), corrugated, plastic pipe extending from the VFP outlet pipe to the Bioswale was excavated and found to be significantly plugged. The pipe was cleaned and the VFP drained. Field "percolation tests" were conducted on the material overlying the treatment media by filling, a bottomless, 18.9-liter (5-gallon) bucket with water and observing the general rate of infiltration. Cores of the treatment media were collected (Brenner, 2003) utilizing 10.2-cm (4-inch), PVC pipe. Next, a "soil probe", about 4.3-meter (14 feet) in length, was excavated to observe the "soil profile" of the media. A "crusty" layer of orange-colored solids, presumably iron-bearing material formed at low pH, was observed overlying the treatment media. Within the compost were pockets of "fresh-looking" limestone aggregate as well as limestone aggregate that was bound by a, then unidentified, "cementing" agent. The underdrain was not inspected. The observation trench within the VFP treatment media was backfilled. As an open channel to convey the VFP effluent was not considered due to future site use, the effluent piping was replaced with Schedule 40 PVC and cleanouts were installed. Interestingly, after this investigation by volunteers from the Slippery Rock Watershed Coalition (SRWC), permeability within the treatment media appeared to be improved and the net alkaline characteristics of the VFP effluent were sustained.

Within one to two years, the permeability again appeared to be decreasing. In July 2004, the SRWC and JWQIC decided to "stir" the VFP treatment media to within about 10-cm (4-inches of the geotextile overlying the inert bedding stone used in the underdrain in an attempt to restore permeability. The raw influent to the VFP was diverted and treated with soda ash briquettes. The VFP was then drained. The "stirring" was conducted utilizing a small, rubber-tired, backhoe. Prior to "stirring", two trenches (lengthwise and widthwise) were cut in the treatment media to again make observations and to collect samples for analysis. Analytical results of the samples completed under the direction of Dr. Art Rose indicated that a portion of the plugging may be related to amorphous Al precipitates and the formation of gypsum which cemented portions of the limestone aggregate (Rose, 2007). Following the field observations, the media was "stirred-and-fluffed" with the backhoe. As previously noted, care was taken to leave about 10-cm (4-inches) of undisturbed treatment media above the separation geotextile in order to protect the fabric. Permeability of the treatment media once again improved.

Nonetheless, after a few years, permeability again decreased. In the summer of 2007, a decision was made to again "stir" the treatment media. The VFP was drained, but due to excessive rains and wet conditions resulting from the development of a spring within the cut slope of the VFP, the small, rubber-tired, backhoe became mired in the treatment media. A small track-type, low ground pressure, excavator was then used to construct a trench through the entire thickness of the treatment media to the geotextile overlying the underdrain and along the length of the VFP. Visual observations indicated that, especially at the base of the treatment media, the spent mushroom compost appeared to have undergone significant decomposition and had a black, clay-like appearance similar to "Play-Doh" or filter cake from a waste treatment plant and which over time had become "pressed" into the permeable geotextile fabric. Slow permeability was noted by small localized "pooling" of water over this layer, indicating that this phenomenon may have played a major role in the observed decrease in the overall treatment media permeability.

Due to the wet conditions only about ¾ of the pond could be stirred. During drying and "stirring" operations, an Aquafix® system using pelletized lime was installed to treat the water instead of soda ash briquettes. An estimated 23-45 kg (50-100 lbs.) of CaO was used per day at an estimated cost of $10-20 per day. The actual "stirring" event is estimated to have cost between $1,500 and $2,000. Monitoring conducted post-rehabilitation indicates that the VFP is treating the water as well and may actually be treating the water better than over the previous 5-7 years. Additional monitoring is necessary, as well as identifying laboratory methods used by the various data sources, in order to validate this observation.

Other minor maintenance conducted at the site over the years included removing iron sludge buildup that had accumulated in the channels and behind weirs, especially that which occurred from chemical treatment during stirring events; erosion repairs; and removing cattails that had clogged the Bioswale. (Plants removed from the Bioswale were used to vegetate a newly constructed treatment wetland at another site.)

In addition, although not necessary for water treatment, "housekeeping" activities have been completed by park staff and volunteers. As the site is located within a Pennsylvania State Park and incorporated in environmental and historical mining education programs, efforts such as; mowing grass, installing and maintaining interpretive signs, installing more attractive flow control structures, etc., have greatly contributed to the popularity and educational significance of the site.

Conclusion

The successful operation of the passive system at the Jennings Environmental Education Center for more than a decade demonstrates that long-term effective treatment of acidic, metal-bearing, coal mine drainage can be realized using passive technologies that include Vertical Flow Ponds with mixed spent mushroom compost and limestone aggregate as the treatment media. Even though the longevity of the treatment media has exceeded original projections, occasional "stirring" has been necessary to sustain treatment performance. Based on the experience gained to date, "stirring" of the treatment media has been the primary maintenance item with a partial and a more complete "stirring" being required during the 13-year period of operation. The more complete, two-day, "stirring" event, performed at a cost of about $2000, has provided a much needed general basis for determining equipment requirements and cost estimates including temporary active treatment expenses for future "stirring" events of the Jennings VFP treatment media. Continued monitoring and maintenance are expected to lead to further developments that focus on sustained performance and reduced maintenance in the applied science and technology of passive treatment.

Acknowledgements

Volunteers, funders, and participants from the following: PA Department of Conservation and Natural Resources; PA Department of Environmental Protection (former PA Dept. of Environmental Resources); Jesteadt Excavating, U. S. Department of Energy; Western Pennsylvania Watershed Program; Shaliston Enterprises, Inc.; Keystone Tall Tree Girl Scout Council; Slippery Rock University; Grove City College; Quality Aggregates Inc.; Amerikohl Mining, Inc.; Hedin Environmental Inc.; CDS Associates, Inc.: Jennings Water Quality Improvement Coalition; Slippery Rock Watershed Coalition; BioMost, Inc.; Stream Restoration Inc.

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