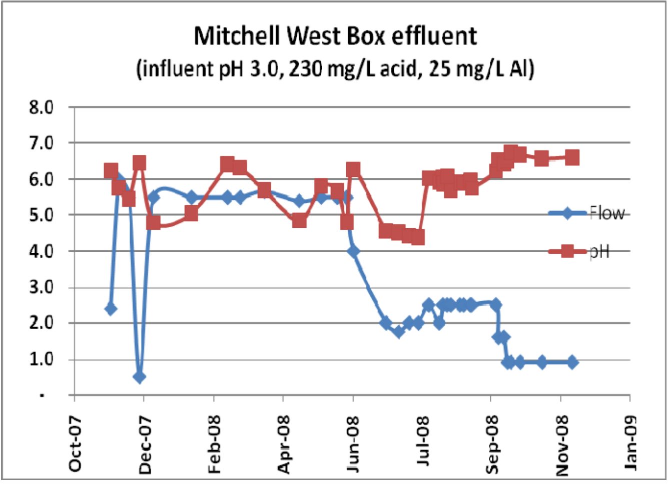
Optimizing the Design and Operation of Self-flushing Limestone Systems for Mine Drainage Treatment

Final Report
December 31, 2008

Prepared by
Hedin Environmental
for
Western Pennsylvania Coalition for
Abandoned Mine Reclamation (WPCAMR)



Project funded by a grant from the
Pennsylvania Department of Environmental Protection
Bureau of Abandoned Mine Reclamation

Executive Summary

The use of limestone in the passive treatment of acid mine drainage contaminated with elevated concentrations of aluminum (Al) is considered problematic because of the tendency of limestone aggregate to be fouled by solids. This project evaluated the effectiveness of an automated flushing system to maintain reactivity and permeability of limestone beds exposed to high concentrations of Al. Two types of flushing systems were investigated. Three systems contained Fluid Dynamics Siphons that automatically flush whenever the bed becomes full of water. Two systems contained AgriDrain Smart Drainage Systems where flushes are controlled by a microprocessor that can be programmed to respond to chemical conditions, water elevation, or time. The systems had been in service as long as five years. Two flows of acid mine drainage were tested. The Jonathan AMD had, on average, pH 3.5 and contained 282 mg/L acidity, 45 mg/L Al, 8 mg/L Mn, and 1 mg/L Fe. The Mitchell AMD had, on average, pH 3.0 and contained 226 mg/L acidity, 27 mg/L Al, 15 mg/L Mn, and 8 mg/L Fe.

None of the limestone beds plugged with solids or exhibited measureable head losses. The regular flushing of a limestone bed to a drained condition maintains porosity sufficient to support unrestricted flow indefinitely. Regular flushing removed a substantial portion of the solids formed in the limestone bed. For limestone beds that discharge water with pH greater than 6, approximately 45% of the influent Al and Fe loads were flushed out as particulates. The remaining metals are retained in the bed as scale on the limestone surfaces that decreases reactivity over time. Without any rehabilitation of the scaled limestone, acidity neutralization eventually decreases to 15-20% of the clean limestone rate. This lowered rate is sustainable for years. The reduced acid neutralization obtained from the regular flushing without any limestone rehabilitation is similar to the neutralization achieved in oxic limestone channels (OLD). Self-flushing limestone beds provide a method for very inexpensive partial AMD treatment without the relief requirements of OLDs.

Fouled limestone was cleaned, rejuvenating the acidity neutralization capacity. Four cleaning events occurred. The most cost-effective cleaning was achieved by agitating the limestone with an excavator in a flowing stream of AMD. Fouled limestone aggregate was rehabilitated to an acid-neutralizing capacity similar to virgin aggregate for as little as $2.50/ton. This compares to $15-20/ton for new limestone delivered to the Tioga County site.

Experiments were conducted that manipulated the hydrologic conditions and the flushing frequency. The best treatment was achieved from a limestone bed operated in a flooded mode. Within 6-8 weeks, however, the treatment performance of the continuously flooded beds declined substantially. Treatment capability was restored when the beds were flushed and drained. The beds provided at least six months of highly effective treatment when operated in a flooded mode with bi-weekly flushing.

Treatment costs were estimated based on 18 months of the experimental results. A long-term cost of ~$359 per ton $CaCO_3$ neutralized was calculated. This cost is about one-third the cost of NaOH treatment and one-half the cost of lime treatment. This cost is 20% greater than lime dosing, but the self flushing limestone bed technology achieves acid neutralization <u>and</u> solids management, while lime dosing only neutralizes acidity.

Table of Contents

Table of Figures

Table of Tables

Introduction

Limestone is the most economical commercially available alkaline reagent for the treatment of acid mine drainage. In terms of neutralizing capacity, it has a 7:1 cost advantage over lime and a 20:1 cost advantage over sodium hydroxide. Its non-hazardous nature allows it be handled and stored without special precautions. It is widely available in Pennsylvania so that in many cases transportation costs can be minimized. Not surprisingly, limestone is the preferred alkaline reagent in passive treatment systems.

Limestone has several features that make its use in AMD treatment problematic. Calcite dissolution is slower and more limited than alternative alkaline reagents. Practical dissolution rates for calcite are measured in minutes and hours, while rates for lime and caustic are measured in seconds. This kinetic feature translates into larger treatment units for limestone-based systems. Limestone dissolution is also limited by solubility constraints that make the generation of water with pH > 8 or containing more than 100 – 300 mg/L alkalinity (as CaCO3) generally impractical. Limestone aggregate can become coated (armored) with metal hydroxide solids and loose a large portion of its acid neutralization capacity. Laboratory measurements suggest that coated limestone is only 20% as effective for acidity neutralization as clean limestone (Pearson and McDonnell, 1975). Al and Fe solids commonly form in the presence of reactive limestone, causing the accumulation of sludge within the aggregate. The sludge lessens porosity and permeability and, if not managed, will eventually plug the bed so that its usefulness for passive acidity neutralization is hydrologically compromised.

The tremendous cost advantage of limestone over chemical alternatives has prompted decades of research focused on finding techniques that can counter its performance drawbacks in passive systems. The most successful recent development is the anoxic limestone drain (ALD) (Turner and McCoy 1990; Hedin et al., 1994b). An ALD is a buried bed of limestone aggregate that is used to pre-treat acidic mine water before it flows into an aerobic passive treatment system. As the acid water flows through the aggregate, calcite dissolution neutralizes proton acidity and generates alkalinity. One of the drawbacks of limestone – its limited solubility – is used to advantage in the ALD because it is possible to install enough limestone in the ALD to last for decades. The ALD is only effective as a long-term passive treatment tool for mine drainage that will not precipitate metal solids with flow through the limestone. The water must be anoxic and cannot contain ferric iron or aluminum. Also, because the alkalinity generation by ALDs is generally limited to 150 – 300 mg/L $CaCO_3$, its use as the primary source of alkalinity generation is limited to AMD with 150 –300 mg/L $CaCO_3$ acidity. Many AMD discharges in northwestern PA meet these criteria and are suitable for ALD treatment.

Discharges not meeting the ALD criteria have been treated with a variety of limestone-based passive systems. The observation that armored limestone is still 20% as reactive as clean limestone has contributed to the Oxic Limestone Channel (OLC) technology (Ziemcheviec et al., 1997). An OLC provides inexpensive partial acidity neutralization in cases where there is sufficient gradient and water velocity to wash solids away and maintain the aggregate porosity. The method is not suitable for generating a circumneutral alkaline discharge. A variety of methods have been developed to pre-treat AMD so that it can be used for alkalinity generation with lessened armoring or plugging problems. The most common approach is the vertical flow pond which utilizes a bed of alkaline organic substrate laid on top of a bed of limestone aggregate. AMD flows down through the alkaline organic substrate where chemical and microbial processes raise pH, consume oxygen, reduce ferric iron to ferrous iron, precipitate aluminum, and generate CO_2 and alkalinity. This water then flows through the limestone aggregate where additional alkalinity generation occurs without armoring or plugging (Kepler and McCleary, 1994). When properly designed and maintained, vertical flow ponds are able to continuously generate alkaline water with low metals with modest operational requirements.

A principle drawback of the vertical flow pond approach is its large land requirements as compared to chemical treatment alternatives. The Babb Creek Watershed Association manages two treatment systems in the Wilson Creek watershed (Tioga County). The Antrim lime plant treats up to 2,000 gpm of AMD in a footprint of about 1 acre. The Anna S Mine Passive Treatment Complex treats up to 1,000 gpm of flow with two passive systems containing eight vertical flow ponds that have a 15 acre footprint. While the passive system has been highly effective for five years and appears to be capable of cost-effective long-term treatment, this approach is simply not amenable at many sites where there is not sufficient land area.

The goal of this project was to test and develop an innovative method for using limestone aggregate for AMD treatment that would avoid plugging and armoring problems in a much smaller footprint than necessary for passive technologies. The project investigated the idea that solids that plug and armor limestone might be removed with flushing, thereby extending the treatment lifetime of limestone aggregate. Flushing systems have been incorporated into vertical flow ponds for a decade, but the effectiveness of the installed systems has been questioned through measurements of solids released during flushes (Rose et al., 2004) and by theoretical considerations of the flushing concept (Weaver et al. 2004). Upon scrutiny, most flush systems are not designed large enough or operated frequently enough to remove a significant portion of the metals solids. This project utilized automated flushing devices that generate high flush velocities and were considered the best available technology for the removal of metal solids in limestone aggregate. The project utilized the flushing devices to experimentally treat AMD containing aluminum and ferric iron with limestone aggregate for 18 months. The ability of mechanical washing to rejuvenate the reactivity of armored limestone was evaluated. This report presents the project's findings, presents design concepts, and evaluates the cost-effectiveness of this innovative treatment technology.

Methods

Water chemistry was determined with field measurements and laboratory analyses. Temperature and pH were measured in situ with a calibrated pH meter. Alkalinity was measured in the field by titration to pH 4.5 using 1.6 N sulfuric acid. Samples intended for laboratory analyses were collected into clean plastic bottles provided by the laboratory (G&C Laboratory, Brookville, PA). Raw and acidified (50% nitric acid) were collected. The standard acidified samples were collected without filtration. In some cases, a second set of filtered samples were collected. The samples were filtered in the field using a 0.22 um membrane syringe filter and immediately acidified. Samples were delivered to the laboratory within several days of collection and analyzed within 3-5 days. The raw sample was analyzed for pH, alkalinity, acidity (hot H_2O_2 procedure), and sulfate. The acidified samples were analyzed for Fe, Al, and Mn. Unfiltered samples were reported as total metals. Filtered sample are reported as dissolved metal concentrations. All methods followed standard methods (APHA, 1999).

The Mitchell flush boxes were monitored for water level, pH, and temperature data with individual In-Situ Multi-Parameter TROLL 9500 LTSs. The devices were hung in the water level control box behind the boards. The devices were programmed to collect information every 10-30 minutes. Data were downloaded onto a laptop computer and analyzed in the office. The pH sensors of each device were calibrated every 2 weeks using premixed buffer solutions.

Flow rates were measured by the timed volume method using a bucket and stopwatch. Flows were measured at the inlet pipes of the Jonathan boxes and the Mitchell boxes. The flow out of the Mitchell tank drain pipe was measured in July 2008 while the tank was being cleaned (and was drained). After modifications to the Mitchell AMD distribution made in October 2008, the total flow to the Mitchell treatment systems (tank and boxes) could be measured with a bucket and stopwatch.

Solids were collected and analyzed for chemical composition. Samples were collected into bottles or plastic bags and dried at 105^oC in a Fisher Scientific Isotemp drying oven to constant weight. The solids were hand ground with a mortar and pestle. The dry powder was provided to Activation Laboratories (Toronto, Canada) for elemental analysis by method 4B. Metals were determined by ICP on ashed samples dissolved in acid. The laboratory reports the analysis of the oxide minerals in the ash. The results provide a quantitative measure the elemental composition of the solid, but not the original mineralogical composition.

Sites

Data were collected from three systems where AMD was treated with limestone beds equipped with automated flushing devices. All three sites have discharges with low pH, low concentrations of Fe, low to moderate concentrations of Mn and high concentrations of Al. Table 1 summarizes the water quality at the study sites.

Table 1. Flow range and average inflow chemistry for the experimental systems.

Site	Flow	pH	Acidity	Fe	Mn	Al
Jonathan (CCS)	1-2	3.54	282	1.1	8.2	44.9
Mitchell Tank*	30-50	2.99	226	8.4	15.0	27.0
Mitchell Boxes*	0.5-5.5	2.99	226	8.4	15.0	27.0

**Mitchell Tank and Experimental Systems have identical source water;*
Flow is gpm, acidity is mg/L $CaCO_3$, metals and sulfate are mg/L

The sites are described below.

Jonathan Run Roll-Off Boxes

The headwaters of Jonathan Run are located east of Snow Shoe in Centre County, Pennsylvania. The stream was seriously degraded in the 1960's during the construction of Interstate 80. Pyritic sandstone was used as fill where the highway crosses the headwaters of Jonathan Run. Soon after construction, acid seeps developed from waste rock piles located on the south side of I-80 and along the culvert that carried the stream beneath the highway to the north. The acidic drainage was, and still is, highly acidic and contaminated with elevated concentrations of Al. Jonathan Run north of I-80 has not supported aquatic life since construction of the highway.

In 2001, the Beech Creek Watershed Association received a Growing Greener grant to investigate the Jonathan Run problem, implement affordable solutions, and to develop a restoration plan for the acid discharges. A thorough assessment of the stream's hydrologic and chemical conditions was completed, the stream channel was reconstructed, the acidic rock pile was reclaimed, and two pilot-scale self-flushing limestone systems were installed to treat the most acidic discharges. These pilot systems continued to operate after completion of the project in June 2003. The performance of the systems was reassessed in 2005 through a study of the Jonathan Run AMD problem by the University of Pittsburgh. The current project supported continued assessment and experimentation with the pilot systems.

The Jonathan pilot systems treat acid water that is collected from the I-80 culvert in the *culvert collection system* (CCS). This flow has low pH, high concentrations of Al and Mn, and low concentrations of Fe (Table 1).

The pilot system consists of two 30 CY metal roll-off boxes that contain limestone aggregate and receive flow from the CCS. The amount of inflow to each box is regulated by individual valves. The boxes operate in parallel and are completely independent of each other. Each box was constructed as follows. Acidic water enters the top of the roll-off, spills onto the limestone aggregate, and fills the container. In the bottom of each container, a 15-inch perforated PVC pipe extends (in solid pipe) through the container liner to a 4 ft diameter concrete vault that contains an automatic self-flushing siphon device (Fluid Dynamic Siphons, Inc.). The pipe provides an unrestricted connection between the roll-off container and the vault. The siphon effluent pipe passes through the vault wall and discharges into a small sedimentation basin. The siphon is triggered when the water level in the container reaches the top of the limestone. When triggered, water rushes from the container into the vault and through the siphon to the sedimentation pond. The roll-off container is emptied in 3.5 minutes at an average flow rate of ~700 gpm.

Photos 1 and 2 shows the boxes and settling basin.

The design parameters are shown in Table 2. The roll-offs were not watertight and were lined with HDPE landfill liner. Both units were filled with ~35 tons of limestone obtained from the Glenn O. Hawbaker Inc. in Bellfonte, PA. The only variation between the units was the limestone specification. One box received AASHTO #1 aggregate (Box 1) and the second roll-off received AASHTO #3 aggregate (Box 3). AASHTO #3 stone is smaller than AASHTO #1. It was hypothesized that smaller limestone would generate more alkalinity because more surface area is in contact with the water. Conversely, it was hypothesized that larger limestone would allow more effective flushing of solids because of the larger pore spaces.

Table 2. Construction characteristics of the flush systems.

	Jonathan Run	**Mitchell Tank**	**Mitchell Boxes**
Construction Date	May 2003	December 2005	October 2007
Construction Type	6,060 gallon roll off container	117,000 gallon concrete tank	6,060 gallon roll off container
Limestone Mass	35 Tons	625 Tons	32 Tons
Limestone Size	AASHTO #1 and #3	AASHTO #1	100% <1", 0% <1/2"
Flush Type	8 inch Siphon (Model 0860)	14 inch Siphon (Model 14108)	AgriDrain Smart Drainage System (8 inch diameter)
Average Flush Rate	700 gpm	2,500 gpm	400 gpm
Drawdown Rate	1.3 feet/minute	0.4 feet/minute	0.7 feet/minute

In 2006, the bulk porosity of the systems was measured by filling each system at a known flow rate while measuring the water level at regular intervals. Measurements began with the water level at the low water line of the siphon (the end of a flush) and ended when the siphon was triggered (the high water line of the siphon). Using this method, the bulk porosity of Box 1 (which includes the roll-off, transfer pipe, and vault) was determined to be 2,537 gallons with a 53 inch drawdown, while Box 3 had a bulk porosity of 2,153 gallons with a 53 inch drawdown. The 18% difference in porosity between the units is attributed to aggregate variation, irregularities in liner placement between the boxes, differential solids accumulation between 2003 and 2006, and measurement error.

A dissatisfactory feature of the Jonathan units is the large volume of water that sits in the transfer pipe, vault, and siphon. This water is not in contact with limestone and cannot benefit from calcite dissolution. Based on calculations of the volumes of the pipe and vault, it was estimated that about 70% of the water in each system was in contact with limestone while 30% was not.

This feature is an artifact of the small containers, site conditions, and large (relative to the container size) siphon.

Samples were collected from the common CCS influent pipe and from each the siphon discharge during flush events. Because it was not possible to always catch the 5-minute flush events, a method for automatically collecting and saving a sample of a flushing event was devised. A hose was installed through the effluent siphon pipe that discharged into the 16 gallon tub. During a flush event, the hose continuously collected a small portion of the flow and discharged it into the bucket. When HE personnel visited the site, the contents of the bucket were thoroughly mixed and samples were collected for field and laboratory analyses.

Mitchell Flush Tank

The Mitchell discharge is located in Tioga County just west of the village of Antrim. The Mitchell discharge is the last significant flow of untreated acid mine drainage to Wilson Creek, a tributary of Babb Creek in Tioga County. A pilot treatment system was constructed and came online in January 2006. This treatment system consists of two deep mine discharge collection systems, a transfer pipe, a flow splitting box, a concrete tank filled with limestone aggregate, a self-flushing dosing siphon in a concrete vault, and a settling pond. The system, which will be referred to as the *Tank* system, was constructed with funds obtained by the Babb Creek Watershed Association from the US Office of Surface Mining and the Foundation for Pennsylvania Watersheds.

The flow splitting box is constructed from HDPE and can produce four flows of piped AMD and also a bypass. The collected AMD flows into the box and passes through a screen that removes large debris and into a chamber that allows water to pass either through an orifice plate or through an overflow pipe. Water passing the orifice plate enters a chamber containing four pipes that can potentially carry equal flows of AMD to four different treatment units. The Mitchell tank utilizes one pipe. Until 2007 the other three pipes were capped. In 2007, one of the extra pipes was uncapped and used to provide flow to the experimental Mitchell Boxes (described below).

The Mitchell acid mine drainage discharge has low pH and elevated concentrations of Al, Mn and Fe (Table 1). Compared to the Jonathan flow, the Mitchell AMD had lower pH, lower acidity, lower Al, and higher Mn and Fe.

The splitter box discharges to an 8 ft tall, 50 ft diameter concrete tank that contained approximately 625 tons of AASHTO #1 limestone (98% $CaCO_3$ limestone from Con-Stone, Centre County, PA). Raw water enters near the base of the tank as a point-source (no flow distribution plumbing). The outflow from the tank is equipped with a network of plumbing on the bottom that consists of 6 inch laterals and an 18 inch header pipe. This header pipe leads to a 10 ft tall concrete vault that contains a self-flushing siphon. This siphon unit has an outlet pipe diameter of 14 inches and a drawdown of 108 inches which allows the water in the limestone to build up to within 6” of the top of the tank before rapidly discharging all of the water in the tank in a 15-minute period. Photos 3 and 4 show the tank under construction and finished.

The siphon discharges approximately 48,000 gallons of water at an average flow of about 2,500 gpm via a buried pipe to a settling pond that contains a rock energy dissipater, a submerged internal berm, and is sized to retain flow for twelve hours. Photos 5 and 6 show the discharge area and settling pond. A video on the Final Report CD shows a tank flushing event ("Mitchell Tank Flush Movie"). The settling pond discharges to a natural channel that carries the flow to Wilson Creek, a major tributary to Babb Creek.

Water samples were collected from within the flow distribution box and from the discharge of the effluent pipe during flushes. Because it was difficult to time site visits to coincide with tank flushes, a hose was installed in the effluent pipe that collected a portion of the flush flow into a tub. The contents of the tub were mixed and water samples were collected for field and laboratory analyses.

The flow into the Tank was considered to be fairly constant because the water level behind the orifice plate does not change substantially (due to the large overflow pipe) and the orifice rarely collected any solids (due to its very low pH). Unfortunately, the position of the orifice hole made measurement of the flow rate at the orifice impossible. Flow measurements are feasible from the tank outlet when it is drained and the siphon is bypassed. Flow was measured in this manner once, in July 2008. The result was 55 gpm. The flow rates into the Tank were estimated from this value, after adjusting for water that was taken in by the experimental units (see below). In September 2008 the orifice plate was modified so that water flowing through the orifice can be captured in a bucket and the amount of water flowing to the treatment units can thus be directly measured.

Mitchell Boxes

Two identical experimental systems were constructed at the Mitchell Site as part of this project. A 4 inch pipeline was installed to convey water from the existing flow splitter box to the system location approximately 300 ft to the east. A 4 inch "T" fitting split the flow between the two systems. The 4 inch pipe was reduced to ¾ inch tubing each system. The tubing was fitted with an end cap with a hole in it. The hole acted as an orifice restriction to regulate flow. End caps with various orifice sized were prepared so that flow rate could be changed by installing an end cap with a larger or smaller orifice. Further fine tuning of flow was accomplished with a ¾ inch ball valve.

Each system consisted of a 30 cubic yard roll off container filled with approximately 30 tons of high quality limestone (98% $CaCO_3$) from Con Stone, Inc (Aaronsburg, PA). The roll-offs were water tight so a liner was not necessary. The limestone was screened so that 100% passes a 1 inch screen while being retained on a ½ inch screen. This is very similar to an AASHTO #5 gradation but the quarry operator did not refer to it as such. For the purpose of clarity the stone gradation will be referred to as AASHTO #5 here. Underdrain plumbing consists of an 18 inch diameter corrugated HDPE culvert pipe cut in half lengthwise. Perforations were created by cutting slots with a chain-saw between every other corrugation. Outlet plumbing was 8 inch schedule 40 pipe. Photos 7 – 10 show the Mitchell boxes during construction.

Unlike the Jonathan Run systems and the Mitchell Tank which both utilize an automatic dosing siphon for flushing, the experimental systems used the AgriDrain smart drainage systems (SDS). The SDS combines a standard AgriDrain inline water level control structure with an actuated gate valve. The actuated gate valve can be programmed to flush either by time or level. Level-based flushing is controlled by two float switches (high and low) which were installed inside an 8 inch piezometer within the limestone bed. Custom programming was performed by AgriDrain to allow level-based flushing. The flushing system discharged 90% of the water in the limestone in 5 minutes at an average rate of 400 gpm. Discharged flow was piped to the existing Mitchell Tank sediment pond. A video on the Final Report CD shows the East box flushing.

The two units are called the *East Box* and *West Box*.

Water samples were collected from a common inlet and from the individual box effluent pipes. Because the boxes flushed on a timer, it was possible to coordinate sampling events to coincide with flush events. However, for those cases where samples could not be collected during a flush event, a flush sampling system similar to the ones installed at Jonathan and on the Mitchell Tank effluent was installed for each box.

Jonathan Self-flushing Units

Performance

The Jonathan units were monitored intensely for 4 weeks after their installation in May 2003. The units provided very good treatment over this short initial period. In 2003 the alkalinity generation rates were 178 and 181 g m^{-2} day^{-1} for Box 1 and Box 3 respectively (Table 3). These rates were sufficient to produce net alkaline effluent from Box 3. Despite the fact that Box 1 produced alkalinity at the same rate as Box 3, effluent from Box 1 was net acidic due to higher influent acidity loading rates associated with slightly higher flow rate.

Little monitoring occurred between July 2003 and 2006. When monitoring resumed, effluent quality from both systems had deteriorated considerably. The alkalinity generation rates for Box 1 and 3 had had fallen to 15% and 20%, respectively, of their 2003 rates. The deterioration was due to decreased reactivity of the limestone, not plugging of the limestone bed. When the units were inspected in 2006, the flushing mechanisms were found to be functional. The siphons were triggering when water elevations reached the top of the limestone and the units flushed at a very high flow rate.

The influent flows to the systems were adjusted in 2006 to determine whether the units could still produce circumneutral effluents. To achieve effluent of similar quality to that produced in 2003, flow had to be reduced to 0.25 gpm for Box 1 and 0.13 gpm for Box 3. These flows are 13% and 8%, respectively, of the flows that produced circumneutral effluents in 2003.

Table 3. Summary treatment performance of the Jonathan Units, 2003 and 2006.

		pH	**Flow (gpm)**	**Acidity (mg/L)**	**Al (mg/L)**	**Acid Load, $g/m^2/d$**	**Acid Removed, $g/m^2/d$**
Box 1 2003	In	3.5	2.0	302	48.4	218	
	Out	5.1		52	34.2	40	178
Box 1 2006	In	3.5	1.6	298	47.2	184	
	Out	4.2		225	35.8	156	28
Box 3 2003	In	3.5	1.6	304	48.0	177	
	Out	6.1		-6	31.7	-4	181
Box 3 2006	In	3.5	1.1	292	46.4	123	
	Out	4.5		141	24.2	86	37

Limestone size

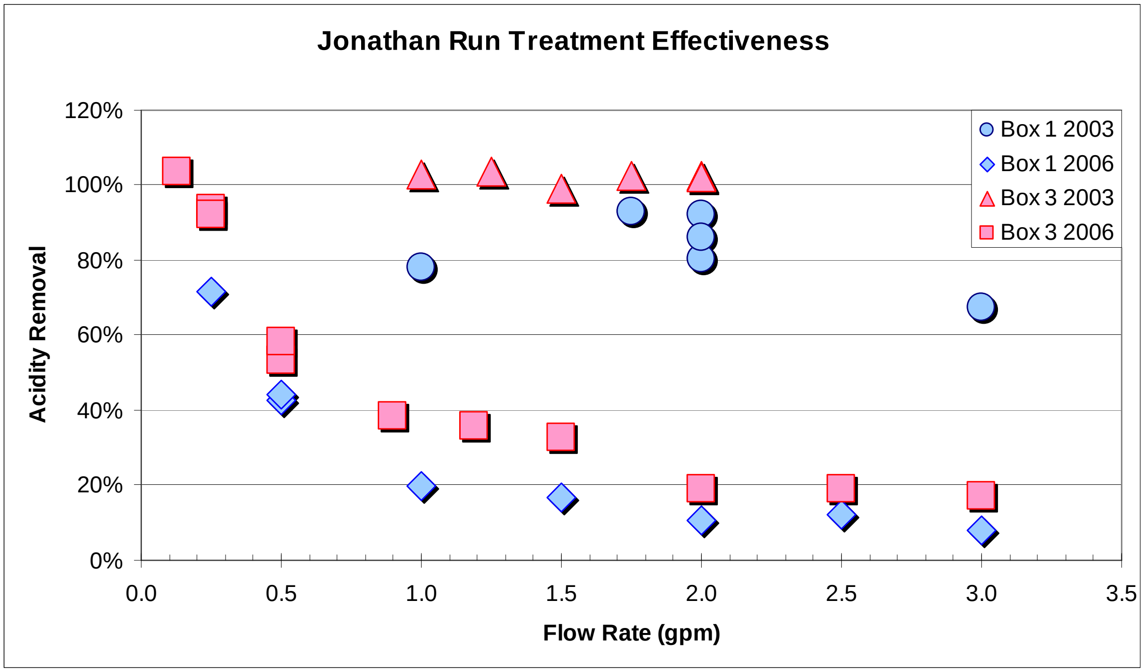
Alkalinity generation occurs on the surface of the limestone particles. Surface area per unit volume increases as particle size decreases. As a result, alkalinity generation is directly related to limestone aggregate size.

Two different sizes of limestone aggregate were used in the construction of the Jonathan Run systems. Box 1 contained AASHTO #1 limestone while Box 3 contained smaller AASHTO #3 limestone. The sizing specifications for AASHTO #1 and #3 are shown in Table 4. This arrangement allowed for a side-by-side comparison of the influence of limestone size on treatment effectiveness. Figure A shows the percent acidity removal for each system at various flow rates.

Table 4. Size and grading requirements for coarse aggregates

	Total Percent Passing							
	4"	**3 ½"**	**2 ½"**	**2"**	**1 ½"**	**1"**	**¾"**	**½"**
AASHTO #1	100	90-100	25-60		0-15		0-5	
AASHTO #3			100	90-100	35-70	0-15		0-5

Figure A Percent acidity removal at varying flow rates by the Jonathan Run units



In 2003 Box 3 produced 24% more alkalinity than Box 1. In 2006 Box 3 produced 68% more alkalinity than Box 1. The change over time is due to the fact that alkalinity generation rates are nonlinear. Alkalinity generation slows as the solution approaches neutral conditions and continues to slow as the solution moves to net alkaline conditions. All of the samples from 2006 represent the fast alkalinity generation rate of a strongly net acidic solution so the results are comparable. However, in 2003 the effluent from Box 3 was neutral to net alkaline while Box 1 was net acidic so direct comparison of alkalinity generation rates is less reliable. Figure B plots influent acidity loading against alkalinity generation rates and reveals that: a) Box 3 consistently outperforms Box 1; and b) both systems experienced considerable loss of performance between 2003 and 2006.

Looking only at 2006 flows greater or equal to 1 gpm (where effluent from both boxes is strongly net acidic) the disparity in performance is greater still. Under these conditions Box 3 neutralized 85% more acidity than Box 1. When flows were less than 1 gpm (and effluent approached neutrality), the disparity was 28% which is comparable to the overall average of 24% measured in 2003.

Figure B. Alkalinity generation rates at varying influent acidity loading rates for the Jonathan Run units.

Flushing

Comparisons of flushing effectiveness between 2003 and 2006 are difficult because by 2006 very little Al was precipitated by the systems. Calculating what proportion of the Al was flushed as particulates relative to what was precipitated will allow for general comparisons to be made. To assess the effectiveness of the flushing, the following equation was used:

$$FE = (\mathrm{Al}^{Eff:tot} - \mathrm{Al}^{Eff:dis}) / (\mathrm{Al}^{Inf:tot} - \mathrm{Al}^{Eff:dis})$$

Where: FE is the flushing effectiveness; $\mathrm{Al}^{Eff:tot}$ = total effluent Al concentration; $\mathrm{Al}^{Eff:dis}$ = dissolved effluent Al concentration; $\mathrm{Al}^{Inf:tot}$ = total influent Al concentration. The denominator is the amount of solids formed with flow through the box. The numerator is the amount of solids contained in the flush.

This equation assumes 100% of influent Al is dissolved, which was verified by analyses of influent samples. Since only solid Al should be affected by flushing, dissolved Al is ignored to compare the amount of solids formed to the amount of solids flushed. The percent of flushable solids removed from the system are shown in Table 5.

In 2003, both boxes removed the majority of Al solids. Box 1 performed better than Box 3 in Al solids removal suggesting that solids removal is directly related to aggregate size. By 2006, Box 1 flushing performance had declined such that Box 1 was removing 10% of the flushable solids while Box 3 was removing 9%. Flushing effectiveness in 2006 was almost irrelevant because both systems produced so few Al solids (due to lessened reactivity of the stone).

Table 5. Flushing effectiveness of the Jonathan boxes.

			Aluminum mg/L			
Box (year)	Count	Average Flow	$\mathrm{Al}^{Inf:tot}$	$\mathrm{Al}^{Eff:tot}$	$\mathrm{Al}^{Eff:dis}$	FE
1 (2003)	5	1.8 gpm	47.7	35.8	1.8	74%
1 (2006)	6	1.0 gpm	47.5	33.8	32.3	10%
3 (2003)	6	1.6 gpm	48.0	31.7	0.4	66%
3 (2006)	7	0.9 gpm	47.2	24.3	22.5	9%

Limestone reactivation

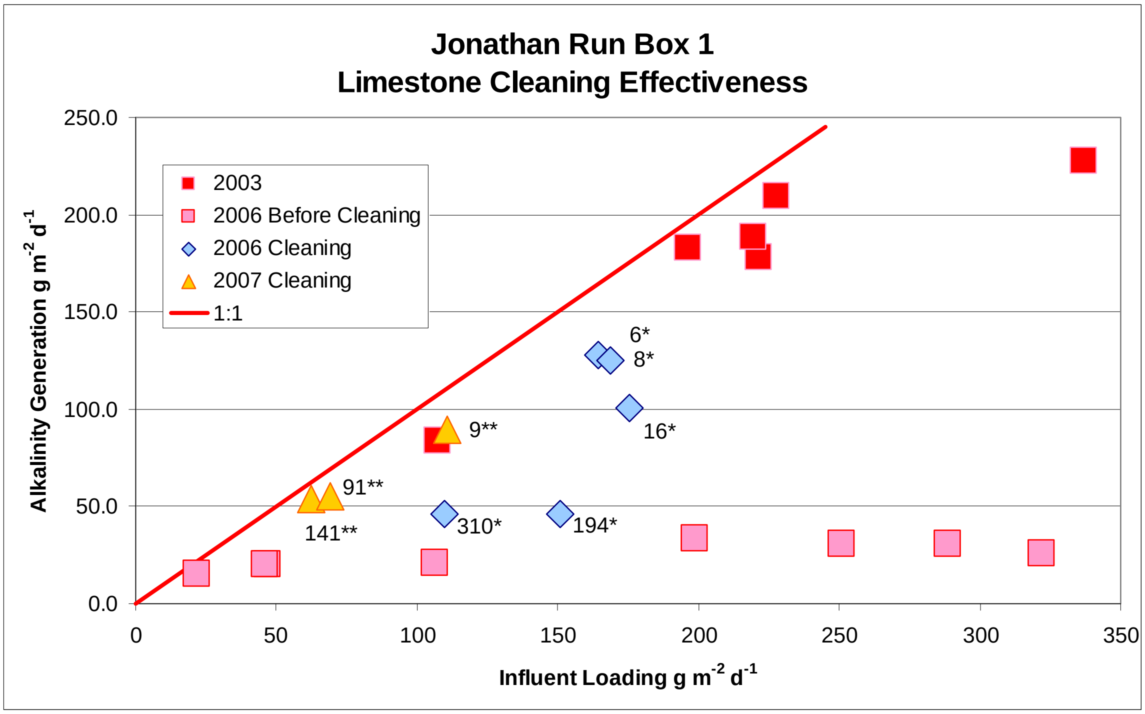
The accumulation of metals solids reduces the treatment effectiveness of limestone. It was hypothesized that removal of the metals solids would restore treatment effectiveness. To evaluate this, limestone in Box 1 was mechanically cleaned by mixing the limestone with an excavator while spraying it with water from a 3 inch pump. Two cleanings were performed, the first on May 24, 2006 and the second on April 3, 2007. Site conditions prevented the excavator from accessing Box 3 so only limestone in Box 1 was cleaned during the first cleaning. Limestone in both boxes was cleaned during the second cleaning. However, Box 3 developed a leak and did not function properly following the cleaning so no post-cleaning flush data are available.

The technique for cleaning the limestone for the 2006 cleaning event involved excavating the limestone from Box 1 and piling it on top of the limestone in Box 3. Fresh water from an adjacent pond was sprayed onto the limestone as it was handled by the excavator. The full flow of the discharge (~25 gpm) was directed into Box 1 so that the system was filling and draining throughout the operation. Photos 11-18 show the excavation and cleaning process.

In 2007 the technique was the same except a pump was not used to spray water onto the stone. Rather, the stone was repeatedly scooped and dropped into standing water as the system filled with water and then flushed.

To assess the effectiveness of the cleaning of limestone in Box 1 the performance was compared to 2003 levels. For limestone self flushing systems, alkalinity generation rates are directly related to acidity loading rates. Figure C shows that in 2003, shortly after treatment system construction, the systems produced significantly more alkalinity at comparable loading rates than it did in 2006. Cleaning the limestone resulted in initial alkalinity generation rates that agree very well with those measured in 2003 suggesting that the treatment capability of the limestone was fully restored.

Figure C. Jonathan Run Box 1 "reactivation".



**days since 5/24/06 limestone cleaning event*
***days since 4/3/07 limestone cleaning event*

Like the high levels of performance observed in 2003, the improvement in performance following the limestone cleaning was not permanent. By June 9, 2006 (16 days after cleaning) the performance had begun to decline. By the next sampling event in December (194 days after cleaning), performance had declined to pre-cleaning rates.

Following the 2007 cleaning event, the system was subjected to loading rates that were one third to one half of the 2006 post-cleaning rates. The system performed at a level comparable to 2003 performance for at least 141 days (Figure C). This is nearly 4 times the duration of the performance improvement in 2006 suggesting that the rate of performance decline in proportional to loading rates. This is anticipated because greater loading rates result in more rapid accumulation of solids within the system which in turn retards alkalinity generation.

A proper maintenance event would involve cleaning of limestone and also replacement of the limestone that had dissolved. No new limestone was added during either cleaning event so the decline in performance is likely more rapid than if fresh limestone had been added. Prior to the 2006 cleaning approximately 1 ton of limestone had dissolved from Box 1. This represents approximately 3% of the original mass or two hours of residence time at a flow rate of 1 gpm.

When the site was visited in February of 2008 for sampling it was discovered that the influent plumbing to both systems had been crushed by a fallen tree. Both systems are inoperable and will be removed by PennDOT as part of their remediation plan for Jonathan Run.

Summary

The Jonathan Run systems clearly established the influence of aggregate size on alkalinity generation in limestone self-flushing systems. AASHTO #3 aggregate generated more alkalinity than the larger AASHTO #1, however AASHTO #1 flushed solids more effectively than the smaller AASHTO #3. The solids removal effectiveness will likely limit the lower range of aggregate size.

The Jonathan systems show that, even with impressive removal of solids, effective treatment is limited and alkalinity generation declines with time. The decline is due to lessened reactivity of the stone due to armoring and scaling by metal solids. The solids can be removed mechanically, and the reactivity of the limestone can be restored.

Mitchell Flush Tank

Performance and Flushing

Monitoring of the Mitchell flush tank began in January of 2006, one month after the system came online. The first flush to be sampled was circum-neutral with minimal dissolved metals. By April effluent quality declined to strongly net acidic with 8-14 mg/L dissolved aluminum.

The Mitchell Tank was severely overloaded during its first two years of operation. Influent acidity loading averaged 371 g m^{-2} day^{-1} or 0.26 ppd acidity per ton of limestone between January 2006 and August 2007. (The Jonathan boxes were loaded at 184 – 218 g m^{-2} day^{-1} and 0.18 – 0.21 ppd acidity per ton LS.) Influent aluminum loading averaged 41 g m^{-2} day^{-1} during the same period. Rose (2002) suggests that VFP-type systems are susceptible to plugging at aluminum loading rates greater than 4 g m^{-2} day^{-1}. In spite of the aluminum loading rates that averaged an order of magnitude greater than the recommended rate, no loss of permeability was observed and no problems with the flushing mechanism occurred.

Table 6: Mitchell Tank Performance January 2006 to August 2007

		pH		**Aluminum (mg/L)**				**Net Acidity (mg/L)**	
Count	Average Flow *	In	Out	$Al^{Inf:tot}$	$Al^{Eff:tot}$	$Al^{Eff:dis}$	FE^1	In	Out
8	55 gpm	3.0	4.6	19.6	11.1	8.0	27%	211	73

[1] *Flushing Effectiveness as calculated with Equation 1*

Table 6 shows the systems performance for the first 19 months of operation. While the loading rates were impressive, the effluent quality was not. Effluent pH declined from 6.3 to 4.4 in less than four months. Over time the proportion of aluminum precipitated (i.e. the difference between influent aluminum concentrations and effluent dissolved aluminum concentrations) declined from 100% in January 2006 to 33% in August 2007. Likewise, the proportion of acidity neutralized declined from 100% to 61%.

The system was able to flush some solids from the bed. However, with the majority of the aluminum remaining in solution there were little flushable solids produced. Comparing the amount of particulate aluminum in the flush to the amount retained shows that the system flushed 27% of the aluminum solids that formed within the bed during this period.

Limestone Reactivation

Over three days in August 2007 the limestone in the Mitchell Tank was cleaned by handling it with an excavator. No pumps were used to spray water onto the stone. A pool was created within the tank (by removing limestone) which was used as a wash basin for cleaning stone. An inflow and outflow of mine water through the tank (and the pool) was maintained continuously during the cleaning. Coated limestone was dumped into the pool and agitated with the excavator bucket to mechanically remove attached solids. The cleaned limestone was stockpiled on top of limestone that had not yet been cleaned until there was sufficient room for the clean stone to be reinstalled without risk of mixing with adjacent coated limestone. As the cleaned limestone was moved back into the system it uncovered more stone to be cleaned. This cycle was continued until all of the limestone was cleaned.

Photos 19-23 show the cleaning process.

Like with the Jonathan Run system, the cleaning of the limestone improved system performance to levels observed immediately after system construction. Also like Jonathan Run, the performance began to decline shortly (Figure D & E). By the October 29th sample, 62 days after the limestone was cleaned, performance (in terms of alkalinity generation) had declined to pre-cleaning levels.

Figure D. a) Alkalinity generation and influent acidity loading after limestone cleaning. b) pH after limestone cleaning

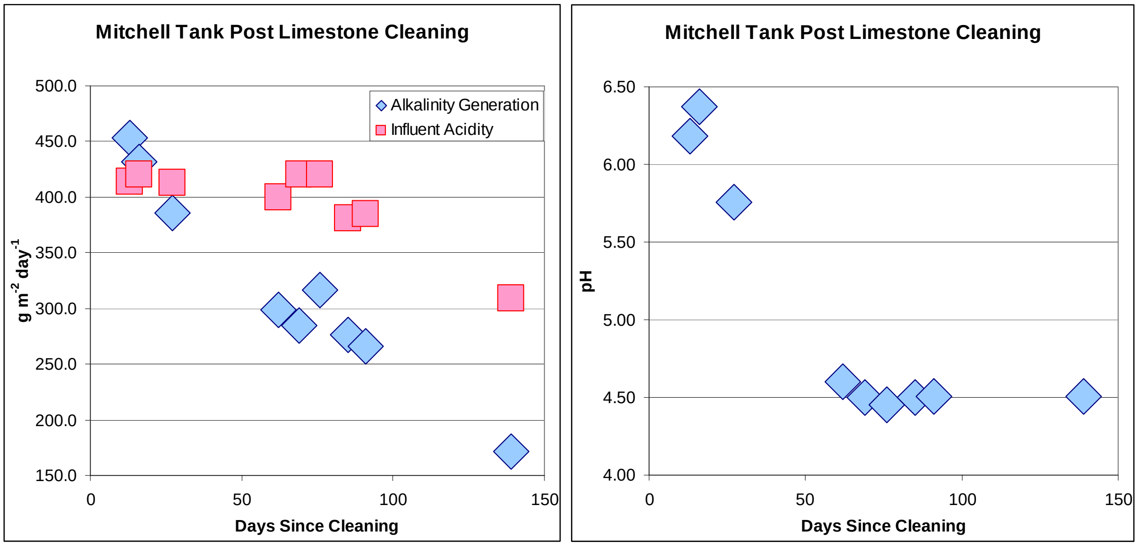
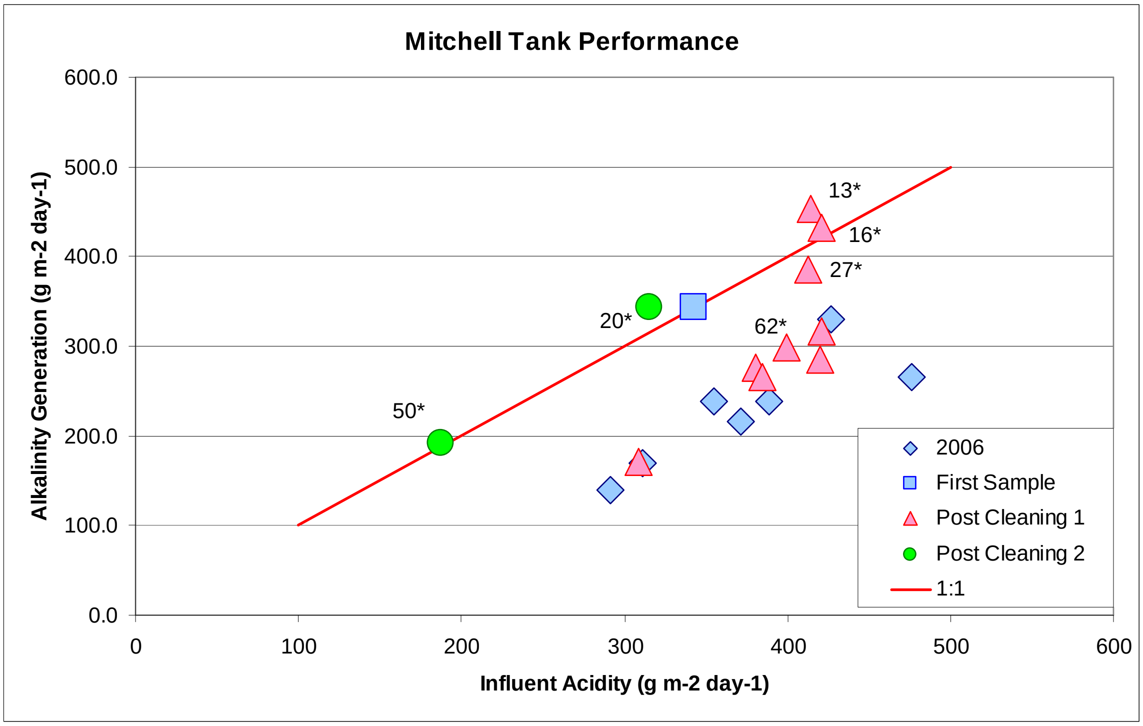


Figure E.. Alkalinity generation and acidity loading before (2006) and after limestone cleaning in August 07 and June 08.



**days since limestone was cleaned*

The cleaning improved the flushing of Al solids from 27% pre-cleaning to 54% post-cleaning. This value remained relatively constant even as the proportion of aluminum precipitated declined over time from 99% to 44%.

A second cleaning of the limestone occurred June 26-30, 2008 using the same procedure as the 2007 cleaning. During the cleaning the underdrain plumbing was removed to facilitate future cleanings. The removal also evaluated the need for an underdrain system in this type of system. The elaborate network of headers and laterals that comprised the original underdrain system was replaced with a simple 18 inch “T” that was capped and perforated (see Photos 3 and 24). In addition, 71 tons of new limestone was added to replace the 36 tons that had dissolved since construction and also boost performance. Flow rate into the system was also reduced after the cleaning in an effort to improve effluent quality. These changes to the system make comparisons to pre-cleaning performance difficult.

The removal of the underdrain system did not deleteriously affect the performance of the box or the removal of solids through flushing (Table 7). The flushate in July and August was net alkaline with low dissolved Al. Based on a comparison of the total Al concentrations, the tank was flushing 55% of the input Al out (as a particulate). These results suggest that underdrain plumbing designs could be simplified or eliminated altogether in future designs.

Table 7. Performance of the Mitchell self-flush tank after second limestone cleaning on June 30, 2008

Date/Location	pH	Flow (gpm)	Acid (mg/L)	Total Al (mg/L)	Dissolved Al (mg/L)	Total Fe (mg/L)
7/20/08 In	3.01	49	220	36.5	NA	7.4
7/20/08 Out	6.18	49	-20	14.1	1.7	3.3
8/19/08 In	2.98	28	229	35.2	NA	8.0
8/19/08 Out	6.18	28	-6	19.8	NA	3.7

NA, data not available

Mitchell Flush Boxes

The experimental flush boxes constructed at the Mitchell Site were designed to advance knowledge learned from the Jonathan and Mitchell tank experiences and to provide a platform for experimentation. Several experiments were conducted that utilized the boxes initially as replicates and later for comparative experiments.

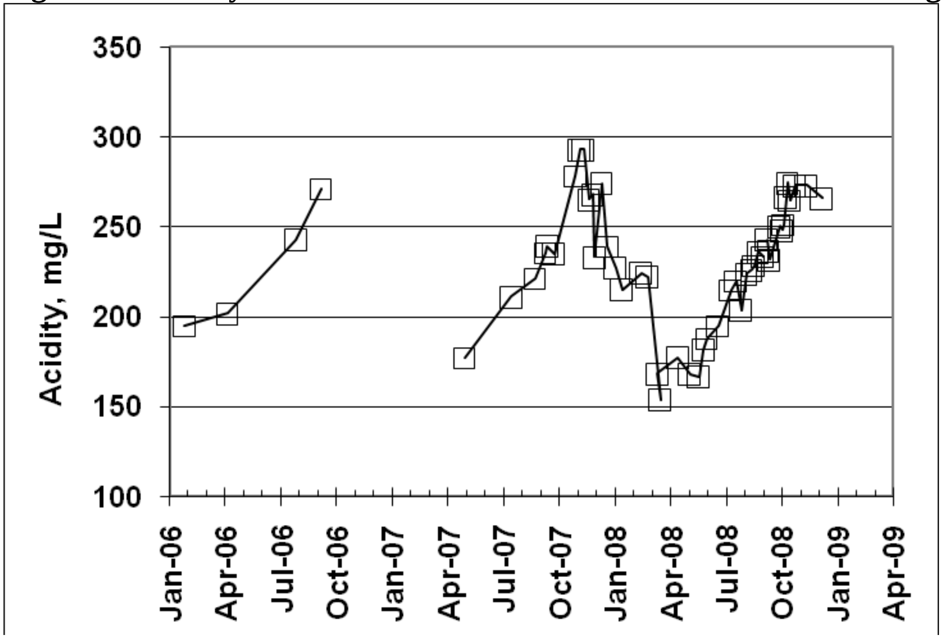
Seasonal Changes AMD Chemistry

The experiments conducted with the Mitchell experimental units were able to control flow rate and flushing modes, but were unable to control influent chemistry. During this project the Mitchell discharge was found to vary seasonally in its chemical condition. Figure F shows the acidity of the discharge through the project. The acidity was lowest in spring (150-175 mg/L) and highest (275-300 mg/L) in fall.

Variation in the influent chemistry complicates the interpretation of some experimental results. When the experiments involved side-by-side comparisons of the boxes, influent acidity variation did not matter. When the results of one experiment were compared to the results of another experiment, the comparisons were complicated if the experiments occurred in different seasons. For example, the initial box experiments occurred in autumn 2007 when the acidity was high but decreasing. Some important experiments occurred in spring 2008 when the acidity was lowest.

Even when acidity concentrations were lowest, the water was severe AMD. The samples with the lowest acidity concentrations still had pH 3.0 and contained at least 20 mg/L Al, 10 mg/L Mn, and 5 mg/L Fe.

Figure F. Acidity concentrations for the untreated Mitchell discharge since 2006.



Treatment Potential in *Level Based Flush* Mode

The first experiment determined the quality of the effluent produced by the setup and its longevity. The systems were operated during this phase at a high flow rate for the following reasons:

- to ensure that limestone fines were removed from the system;
- accelerate passage of the "honeymoon" period;
- to determine what indicates "failure" and how the "failure" occurs.

The boxes were treated as replicates during this phase of the research. Both boxes filled and drained based on water level much like a typical self-flushing system equipped with an automatic dosing siphon. This mode is referred to as *level based flushing* or LBF. When the project was designed, the anticipated "design flow rate" (the rate at which an alkaline effluent is produced for months) was anticipated to be 1 to 2 gpm. The boxes were loaded with 5.5 gpm flows and run until "failure," which was defined as an effluent with pH less than 5. At the 5.5 pgm flow rate the average influent acidity loading averaged 468 g m^{-2} day^{-1} for both boxes. (For comparison, the Jonathan loadings were ~200 g m^{-2} day^{-1} and the Mitchell tank loading was ~370 g m^{-2} day^{-1}.) The pH of the effluent from both boxes declined to <5 after 90 days of high loading. Table 8 shows the average performance over the entire period while Figure G shows effluent pH measurements.

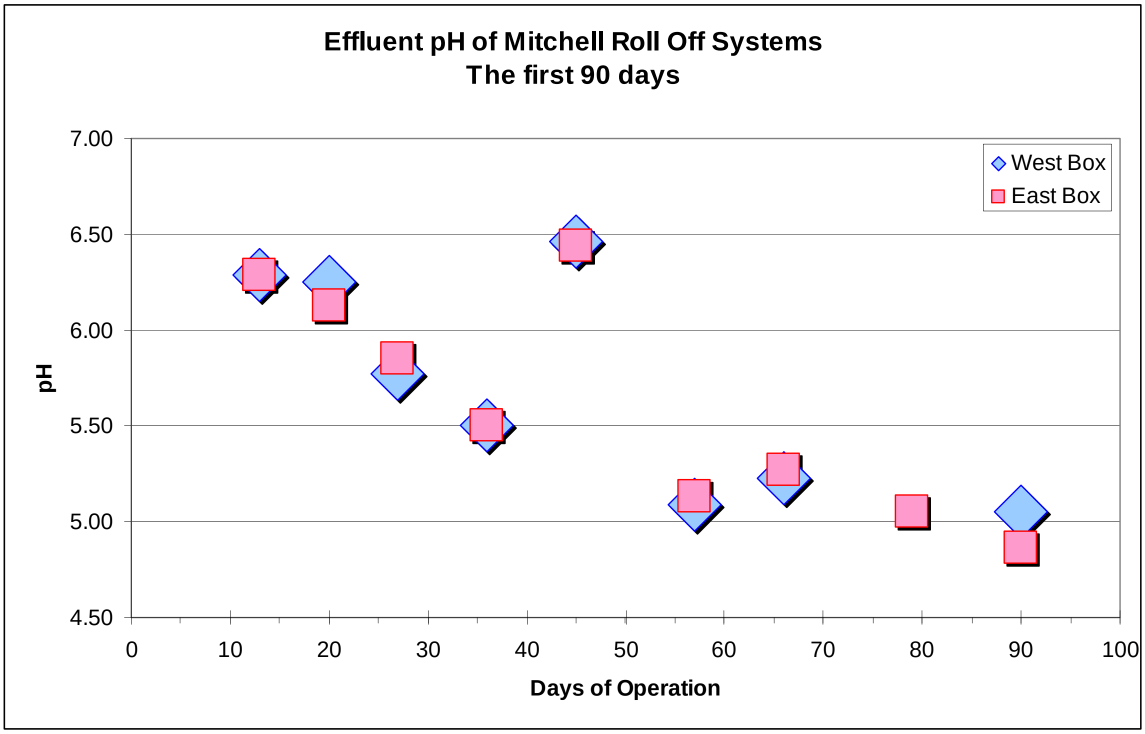
The systems performed identically giving confidence that the boxes were replicates and could be used for comparative experiments. The effluent quality was consistent between both systems even when the flow rate was lowered from 5.5 gpm to 0.5 gpm then returned to 5.5 gpm as shown in Figure G.

Table 8. Average performance by the Mitchell boxes during overloading experiment (days 0-90). The boxes were operating in the LBF mode.

System	n	Flow (gpm)	Influent pH	Effluent pH	Influent Acidity (g m^{-2} day^{-1})	Acidity Removal (g m^{-2} day^{-1})
West	8	4.6	2.98	5.71	468	441
East *	8	4.6	2.98	5.68	468	443

**Omits one sample of East Box collected on a day when West was not sampled*

Figure G. Effluent pH for the Mitchell boxes during initial loading.



** the increase in pH on day 45 was due to a temporary intentional decrease in flow rate to both boxes*

Treatment Potential in *Time Based Flush* Mode

The initial setup programmed the flushing mechanism to flush every time the boxes became full of water and reached a predetermined level (LBF). In this mode the box is empty half of the time and the residence time in the limestone is ½ of its theoretical maximum (pore volume divided by flow rate). To maximize residence time while still providing solids removal, an operational mode was developed that allowed the box to fill completely and discharge in this flooded mode. After a pre-set period of the time, the box was flushed to empty. The operational set-up was possible because the AgriDrain Smart Drainage System allows flushes to be defined based on water level or time. This mode is not possible with the siphon flush devices. Flushes were programmed to occur on Mondays and Fridays. This mode is referred to as *time based flush* mode, or TBF. The 3-4 day flush interval was chosen for sampling convenience.

An experiment was conducted to determine the effect of the TBF mode on discharge quality. Between February 11 and February 25, the East box discharged continuously with sporadic flushes to empty. During this experiment, the West Box was not flushed in order to determine the influence of flushing on system performance. This experiment is discussed in the following section.

Figure H. Effect on effluent pH of shifting from a level based flush mode to time based flush mode.

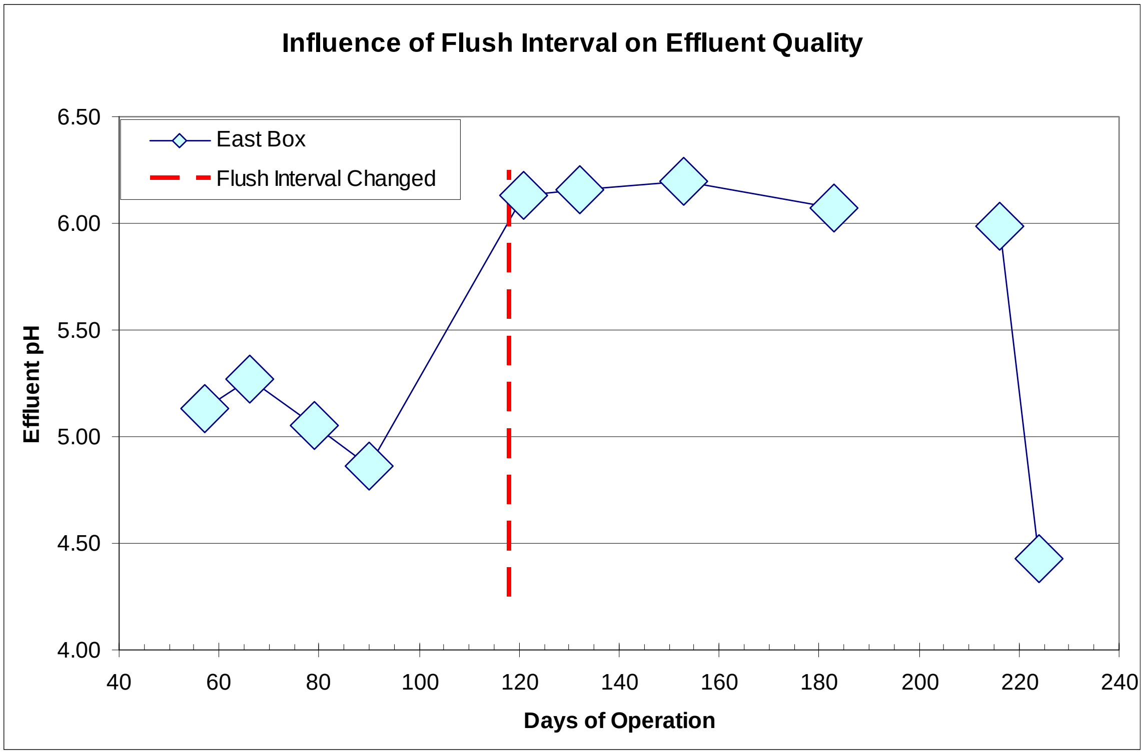


Table 9. Comparison of East Box performance in LBF and TBF modes

Flush Mode	Days	n	gpm		pH	Acid mg/L	Acid Rem g m^{-2} day^{-1}	% Acidity Removal
Level Based	61	4	5.5	In	3.02	244		84%
				Out	5.05	38	417	
Time Based	98	5	5.5	In	3.06	185		100%
				Out*	6.11	0	374	

**Excludes 5/27/08 (day 224) sample. Including this sample results in pH 5.83, Acidity 13 mg/L, Removal 353 g* m^{-2} *day*$^{-1}$ *(93%)*

The change in flow regime resulted in immediate improvement in effluent water quality. Figure H plots the effluent pH of the East Box over time. Table 9 compares the East box performance in both modes. Following the change in flush interval the effluent pH increased from < 5 to 6.1. Acidity removal improved from 84% to 100% as a net alkaline discharge was produced.

The absolute acidity removal rates were higher for the LBF mode because of a difference in influent acidity during the experimental periods. During the LBF data collection period (fall 2007), the raw discharge was at its seasonal maximum acidity leading to very high influent loading rates. When the first TBF experiment was conducted in spring 2008, the acidity of the discharge had declined. This is reflected in Table 9 which shows that the average influent acidity was 32% higher during LBF operation than during TBF operation.

Furthermore, the timing of the experiment occurred during the transition from "honeymoon" period to a more steady-state performance. As a result performance expectations should be raised slightly for LBF and lowered slightly for TBF. The degree to which they should be adjusted cannot be quantified with the available data. Regardless, the impact of these adjustments would be to further solidify the conclusion that a system operated with TBF will outperform a LBF system.

The decline in performance at the end of the experiment was unexpectedly rapid. A sample collected on May 19 showed effluent pH from the East box was 6.0. Eight days later on the 27th, the pH had fallen to 4.4. After this date the pH remained well below 6.0 despite reducing the flow from 5.5 gpm to 2.0 gpm.

The Importance of Flushing

A side-by-side experiment was planned in which one box would be flushed and the other would be allowed to continuously discharge in a flooded mode, but without flushing. In February 2007 the actuator that flushes the West Box malfunctioned causing this experiment to begin ahead of schedule. The East Box was programmed to fill and discharge as in a vertical flow pond but flush to empty (5 minutes) every Monday and Friday. With the West Box flushing mechanism inoperable, it was allowed to discharge continuously (in flooded mode). The results were surprising.

Immediately following the cessation of flushing, the effluent quality of the West Box improved dramatically. The two systems, which had performed identically in the past, were now diverging strongly in performance (Figure I). The West Box effluent steadily declined in quality, becoming net acidic in about 30 days. A steady decline to net acidic effluent from the West Box is also evident in pH measurements taken over this timeframe. Figure J plots both lab reported pH and pH values from continuous monitoring devices over time.

The experiment demonstrated that flushing was a necessary component of obtaining good treatment performance from a flooded limestone bed. Without flushing, there was a short term improvement in treatment effectiveness followed by a substantial decline over the next 60 days. With periodic flushing, a good effluent quality was maintained through the 60 day period. When periodic flushing was resumed, the effluent quality rapidly improved.

Figure I. Comparison of the effluent net acidity when the Mitchell boxes were operated in different flushing modes. (negative values indicate better treatment)

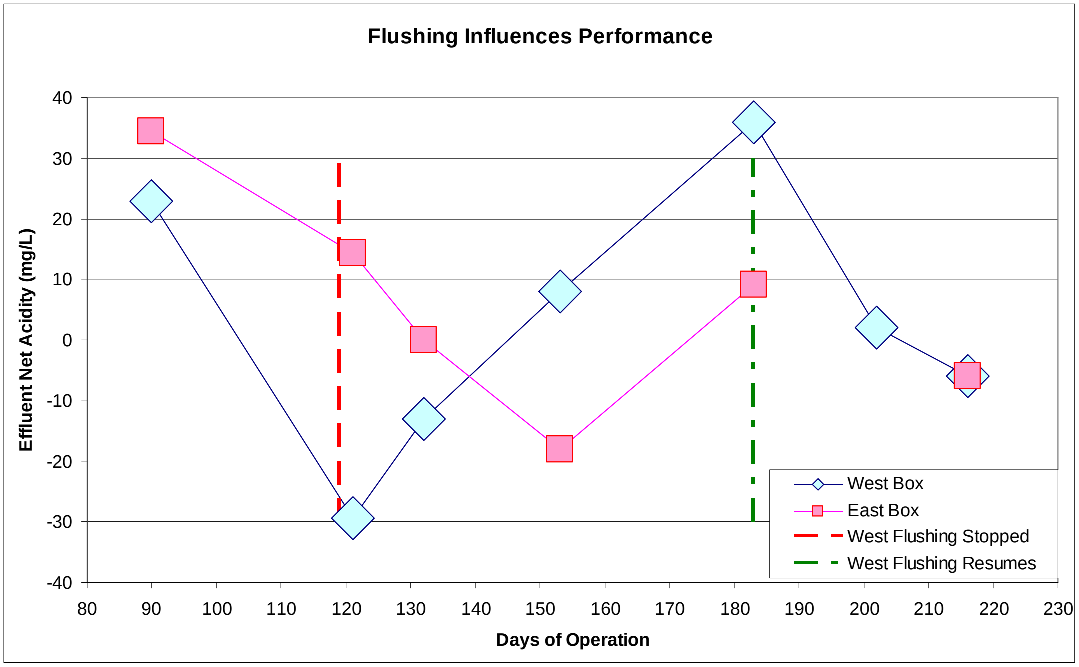
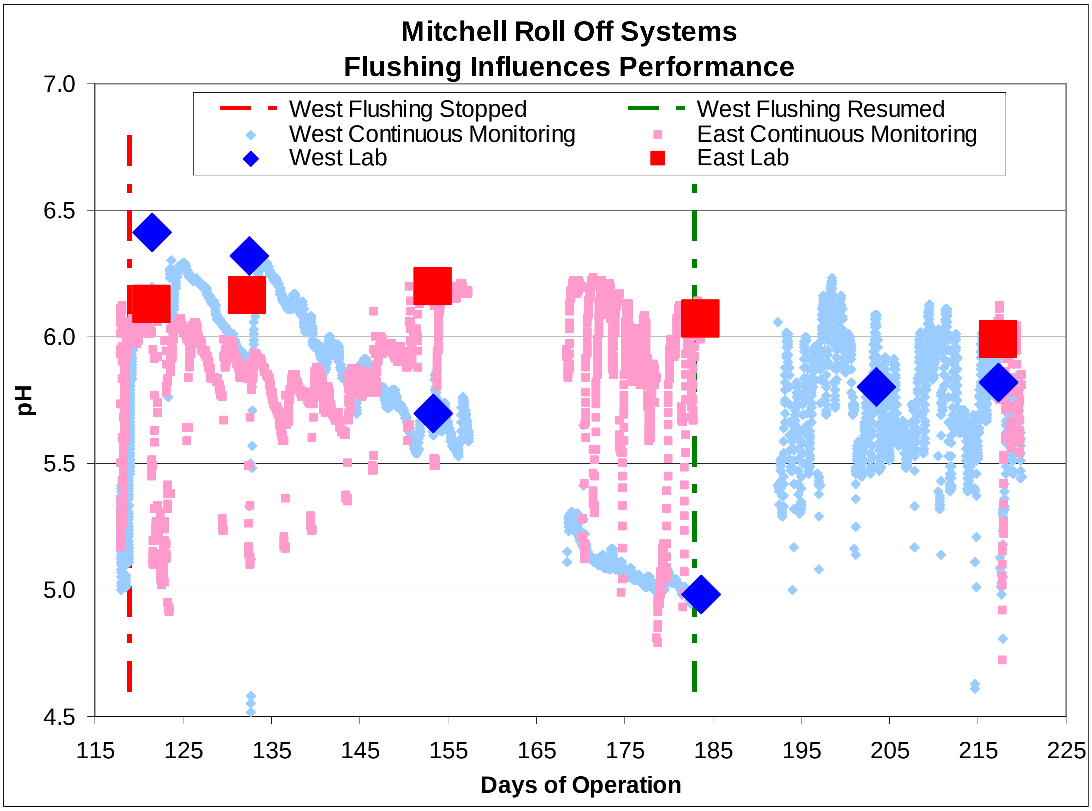


Figure J. Comparison of TBF mode (East Box) and no flushing (West Box)



"West Lab" and "East Lab" are laboratory reported pH values. On day 132 the West Box was flushed to empty to allow for replacement of a faulty actuator.

Flow distribution

Following the initial overloading experiments the flow into the boxes was reduced to determine the treatment capacity of the boxes with fouled limestone. The flow into the West Box was lowered to an average of 1.9 gpm. During this period (days 254 to 286) the effluent quality declined steadily to pH 4.4. On July 28, 2008 (day 286) a simple flow distribution system was installed to diffuse the influent flow over a larger portion of the limestone area. Photo 25 shows the flow distribution system which consists of a ¾ inch diameter PVC pipe with 3/32 inch perforations. The flow distribution system produced significant improvement in effluent quality raising effluent pH by about 1.5 units (Figure K).

When the flow distribution system was installed, flow rate was also increased by 25% to 2.5 gpm. Taking this into account, the improvement in performance is greater still. Comparing performance on a loading per unit area basis, the West Box improved from an average alkalinity generation rate of 103 g m^{-2} day^{-1} pre-distribution to 215 g m^{-2} day^{-1} post-distribution (Figure L). On a percent acidity removal basis the West Box improved from 70% removal to 100% removal. Table 13 summarizes pre and post-distribution performance.

Figure K. West box effluent pH before and after influent flow distribution.

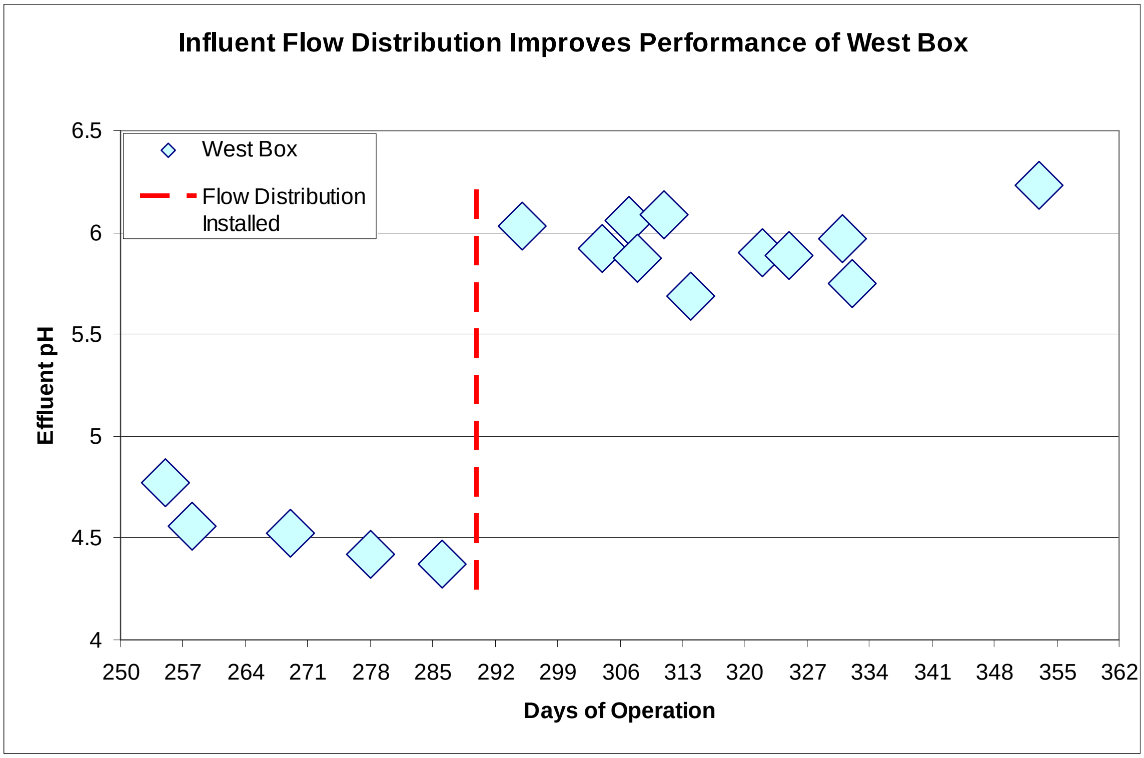


Figure L. Influent acidity loading and alkalinity generation rates before and after influent flow distribution.

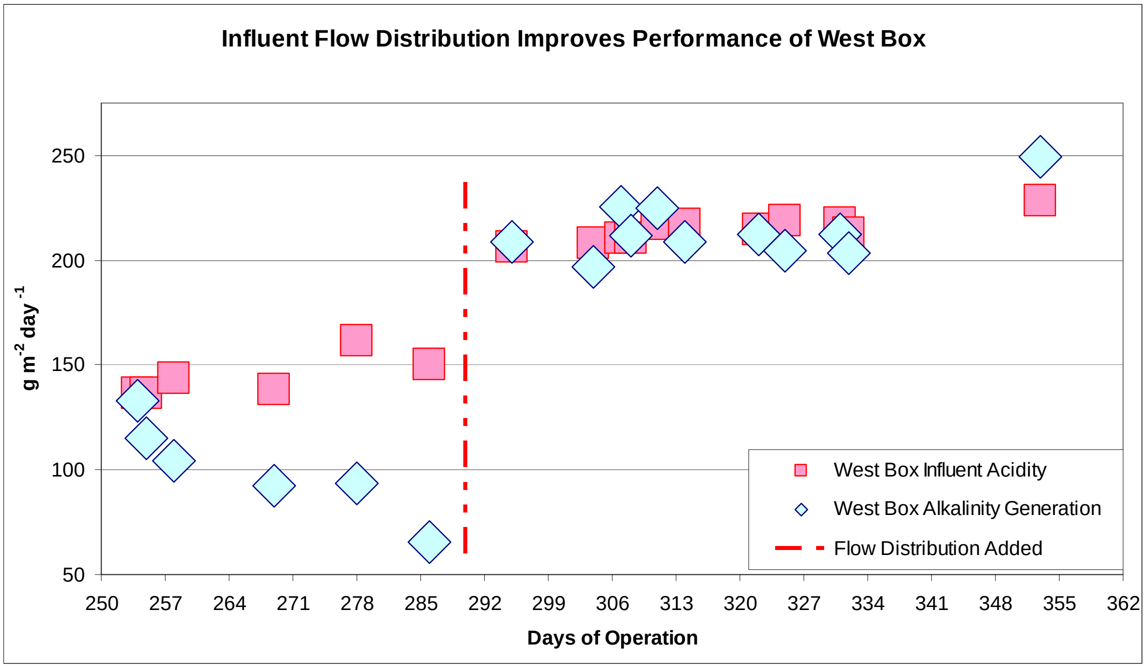


Table 10. West Box performance before and after influent flow distribution.

Time Frame	**flow gpm**	**Days**		**n**	**pH**	**Acid**	**Acid load g m^{-2} d^{-1}**	**Alk gen g m^{-2} d^{-1}**
Pre-distribution	1.9	32	In	4	2.99	208	145	
			Out	6	4.75	61	42	103
Post - distribution	2.5	67	In	9	2.98	234	215	
			Out	11	5.95	0	0	215

"Alk gen" is alkalinity generation

The improvement in performance appears to extend well beyond the 62 days shown in Figures K and L. New experiments began after this point so the data are not included in assessment of the influence of flow distribution on performance. However, the improvement in performance resulting from influent flow distribution relative to performance without influent flow distribution is believed to be permanent.

Limestone Reactivation

On June 30, 2008 the limestone in the East Box was cleaned using similar techniques to those employed at Jonathan Run and the Mitchell Tank. The small size of the system and limited space available at the site led to the decision to utilize a stone box for cleaning the limestone. A stone box is simply a heavy-duty steel box that is commonly used in utility installations for aggregate management and storage. The stone box was easily moved (with the excavator), which increased the efficiency of the cleaning. The use of the stone box provided several cleaning advantages:

- the limestone was not placed on the ground so limestone loss was minimal;
- the limestone was not contaminated with debris or soil;
- mechanical agitation took place in the stone box protecting the roll off container from damage.

Photos 26-28 show the cleaning process which involved directing raw water into the stone box where the limestone was cleaned.

Following the cleaning the flow rate into the East Box was adjusted to 2.0 gpm and as expected, the performance of the unit improved significantly. Figure M shows the pH before and after cleaning.

Figure M. Effluent pH of the East Box before and after limestone cleaning

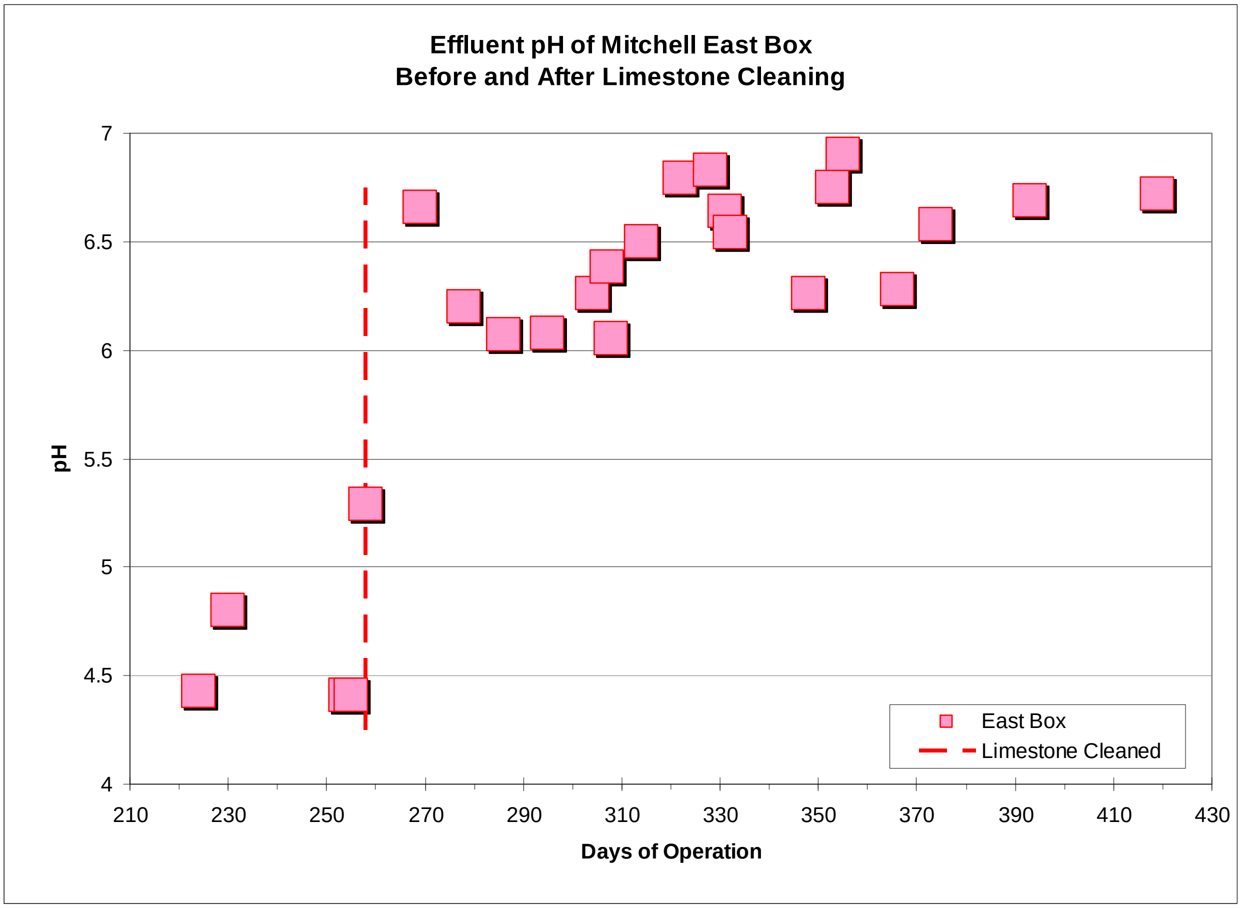


Table 11 shows performance before and after cleaning. Comparing performance on a loading per unit area basis, the West Box improved from an average alkalinity generation rate of 150 g m^{-2} day^{-1} pre-cleaning to 209 g m^{-2} day^{-1} post-cleaning. The rate increased even though influent loading was lower post-cleaning. On a percentage basis, the East Box removed 79% of influent acidity before the limestone was cleaned and 118% after.

The cleaned stone maintained a good effluent (at 2 gpm) until the end of the project 161 days after its cleaning with no sign of decline (Figure M).

Table 11. East Box performance before and after limestone cleaning

Time Frame	flow gpm	Days		n	pH	Acidity	Acid load g m^{-2} day^{-1}	Alk gen g m^{-2} day^{-1}
Pre-cleaning	2.7	28	In	2	3.0	191	190	
			Out	3	4.83	40	40	150
Post - cleaning	2.0	161	In	18	2.95	240	177	
			Out	19	6.52	-44	-32	209

Mn Removal

As the flow rates into both boxes were lowered in an effort to produce alkaline effluent, manganese removal became apparent. The final experiment with the West box explored whether a discharge could be produced that could satisfy the Mn limits of a typical mine water NPDES permit. These limits are: 2 mg/L Mn monthly average, and 4 mg/L Mn daily maximum. The box was operated in a *TBF* mode at 0.9 gpm flow rate. Treatment effectiveness was evaluated from effluent samples collected during flooded conditions. Table 12 shows the results. Effective Mn removal was attained. The average discharge contained 2 mg/L Mn and the highest value was 3.7 mg/L.

The average Mn removal rate for the data in Table 12 is 4.6 g m^{-2} day^{-1}. This value is higher than published values for passive Mn removal in wetlands (0.5 – 1.0 g m^{-2} day^{-1} (Hedin et al. 1994b)). It is similar to Mn removal rates that the authors have measured at other sites where limestone beds are used to treat water contaminated with Al and Mn.

The discharge during this final experiment with the West box would have satisfied most NPDES permits. The limestone in this box was never washed. This result suggests that the *TBF* mode at low flow loading rates could provide a high quality effluent for at least two years before limestone cleaning became necessary.

Table 12. Influent (average) and effluent chemistry for the West Box between October and December 2008. Flow on all dates was 0.9 gpm.

Location and Date	pH	Acid mg/L	Fe mg/L	Al mg/L	Mn mg/L
Avg. Influent	2.93	270	11.4	30.8	18.1
Effluent 10/13	6.52	-67	0.5	1.3	1.5
Effluent 10/24	6.70	-87	0.3	0.7	1.0
Effluent 11/12	6.58	-46	0.4	0.8	1.5
Effluent 11/16	6.76	-69	0.8	1.7	2.8
Effluent 12/8	6.62	-38	3.2	1.0	3.7
Avg. Effluent	6.64	-61	1.0	1.1	2.1

Metals Solids Discussion

To better understand the nature of metals solids accumulation and removal from oxic limestone passive treatment systems, excavations were performed on four of the five systems that are the subject of this study (Jonathan Run Boxes 1 and 3, the Mitchell Tank and the Mitchell East Box). During these excavations visual assessment of the solids within the systems was made and solids samples were collected for analysis.

In all of the systems the accumulation of solids appeared to be uniform throughout the aggregate bed. Excavations adjacent to underdrain plumbing showed no noticeable difference in solids accumulation. Even aggregate located within inches of an underdrain perforation showed solids accumulation similar to all other areas of the aggregate bed (Photo 16). This casts doubt on the notion that sufficient velocities can be generated to dislodge accumulated solids from the limestone surface since limestone around the plumbing should experience longer flushes at higher velocities than other locations in the bed.

At least two general types of metals solids appear to be formed in oxic limestone beds exposed to Al and Fe contaminated water. The first type is a scale that coats the surface of the stone and is often referred to as “armoring”. The scale is brittle and can be flaked off of the limestone surface even when wet (Photo 29 and 30). The second type of metals solid consists of suspended solids that have precipitated within the aggregate void spaces. These suspended solids appear as low density “fuzz” that gradually fills the void spaces (Photo 31). Unlike the scale-type solids, the suspended solids flow easily and do not adhere to the limestone surface.

Solids Chemical Characteristics

Table 13 shows analyses of solids collected from the limestone systems during limestone excavation and cleaning events. Because of the difficulty collecting suspended solids, most of the samples were dominated by more easily collected scale. The “Mitchell Box East” was solids remaining in the stone box after the limestone was washed and cleaned.

The table shows the percentage of each mineral in the ash and provides a good approximation of the relative amounts of each element. The Loss on Ignition (LOI) shows weight loss during ashing. The samples were dried ($105^{o}C$) before laboratory submission, so LOI should primarily represent the water content of the metal hydroxides and the CO_2 content of the calcite. For example, $Al(OH)_3$ transforms at high temperature to Al_2O_3 as shown below:

$$2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O$$

where the water loss is 35% of the original $Al(OH)_3$ weight. This loss is measured in the LOI. To determine the quantitative amounts of the minerals in the original samples the mineralogy must be known. Mineralogical analyses were not done for the samples.

All of the samples were dominated by Al, Ca, Si, and Fe. The source of Al and Fe is the mine water. Water sampling indicated that both metals were retained in the beds. The Mitchell AMD contained more Fe than the Jonathan AMD and the solids followed this pattern. The source of Ca is certainly the limestone. The calcite surface must be weakened as it appears to be flaking off with the metal solids in most samples. Silicon (Si) is the second most prevalent element for every sample. Its source is unknown. The limestone is 98% $CaCO_3$. The remaining 2% is partially silicate. It is possible that the silicate component of the limestone is insoluble and remains on the stone surface after the $CaCO_3$ is dissolved and diffuses away. This silicate would then be passively incorporated into the metal solids that form at the alkaline stone surface. An alternative explanation is that the Si is precipitating from the mine water with the Al and Fe solids. Mine waters commonly have 5-20 mg/L Si and the precipitation of Si under alkaline conditions is known to occur in natural waters. The Si content of the Mitchell AMD is not known. The precipitation of Al and Fe silicates in AMD systems has not been reported previously. Evaluation of this mechanism requires an independent geochemical study.

All of the solids analyzed were diverse mixtures of elements. None of the samples were as pure as alkaline Fe sludges, which can be 80% Fe_2O_3 (with the balance being largely LOI). There does not appear to be any opportunity to produce a marketable product from the solids that are removed when the limestone beds are cleaned. The solids will need to be disposed of, probably through burial.

Table 13. Composition of solids collected from limestone beds during excavation

	Fe_2O_3	**Al_2O_3**	**MnO**	**SiO_2**	**CaO**	**MgO**	**K_2O**	**S**	**LOI**	**Total**
	%	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
Jonathan Inlet	2.2	19.6	1.0	29.7	14.3	1.6	1.2	1.5	25.5	95.5
Jonathan Surface	1.6	36.9	3.5	16.9	2.3	0.5	0.5	2.8	36.0	98.6
Jonathan Mid	1.2	43.6	0.8	11.0	1.4	0.3	0.3	5.1	39.8	98.5
Jonathan Bottom	2.3	29.3	0.5	14.2	11.6	0.8	0.6	3.4	33.1	92.6
Mitchell-A	1.2	8.3	0.4	18.9	31.0	0.7	1.1	0.1	34.4	96.6
Mitchell-B	2.2	9.4	0.2	22.5	29.4	0.7	1.2	0.2	29.3	95.6
Mitchell-C	10.2	25.4	0.8	23.5	6.8	0.4	1.3	2.4	29.8	99.0
Mitchell-D	4.5	21.9	2.5	20.4	12.1	0.6	1.0	1.4	31.8	95.3
Mitchell Box East	8.0	29.1	1.5	20.2	6.2	0.5	0.7	1.7	30.8	97.4

Effects Of Solids On Bed Hydrology

The two types of solids (scales and suspended solids) impact treatment system performance in different ways. Scale reduces alkalinity generation by forming a physical barrier to calcite dissolution. Scale generally does not cause loss of permeability because scale thickness eventually reduces calcite dissolution to the point that metals precipitation stops and thus, scale accumulation stops. The large open void spaces observed in the Mitchell Tank are shown in Photo 32. As long as the average void space diameter is greater than twice the scale thickness, permeability will be maintained. At all three aggregate sizes tested, the pores are large enough to prevent plugging off by scale. Only very fine limestone aggregate or aggregate with a broad range of particle sizes would suffer permeability loss from scale accumulation.

Suspended solids, on the other hand, reduce treatment system performance by forming a barrier to fluid flow within the void spaces. While this may be the early stages of plugging, the loss of permeability created by suspended solids is extremely small and would not result in headloss observable through casual measurement. What the suspended solids do is create headloss between individual void spaces causing the formation of “dead zones”. The “dead zones” grow as more solids precipitate within the void spaces. The individual dead zones coalesce into larger and larger dead zones.

Eventually the region of active fluid flow through void spaces is restricted to a column directly connecting the influent location and the nearest underdrain pipe. Concentrating the flow in this column increases void space velocities producing what is essentially a continuous flush that carries the low density suspended solids out of the system. By the time this condition is reached the effective residence time has been so drastically reduced that essentially no treatment is occurring. With minimal treatment only negligible metals precipitation occurs and plugging is avoided.

The strongest evidence for the dead zone theory came after the West Box was operated without flushing (see Figure I). The effluent had declined to pH 5.0 with 36 mg/L acidity. When the system was flushed the flush water had a pH of 6.4 and net acidity of -19 mg/L. The fact that the net acidity of the effluent was much more acidic than the flush suggests that the flush was releasing water that had substantially longer residence time than the effluent flow. In essence, the flush was emptying the dead zones where the void space water had reached chemical equilibrium. Flushing disrupts these dead zones and rejuvenates the limestone bed until the zones reestablish.

Clearly plugging of oxic limestone passive treatment systems can and does occur. Plugging will occur under a number of conditions such as:

- The flow path between the influent and nearest underdrain pipe is long enough to allow metals precipitation to occur resulting in a continuous dead zone perpendicular to the flow direction
- Suspended solids settle within the void space spaces over time forming a more robust obstruction to fluid flow.
- Void space spaces are smaller than twice the maximum scale thickness

The relationship between suspended solids and scale is unclear. It is possible that suspended solids can become scale over time through settling or wetting and drying cycles associated with flushing. What is clear is that the vast majority of solids removed by flushing are suspended solids which easily flow out of the limestone bed. The amount of scale removed by flushing is negligible. The challenge then becomes designing systems that efficiently remove suspended solids while still producing good effluent quality.

Metals Solids Management

The design and operation of the Mitchell boxes represent a substantial advancement in solids management in passive limestone systems. The use of relatively small (0.75 inch), uniformly sized aggregate and a modified flushing interval were key features in optimizing system performance.

In *LBF* mode (when comparing contemporaneous samples), the two systems flushed essentially the same amount of Al solids with the West Box removing an average of 33% of Al solids and the East Box removing 32%. Retention averaged 64% for both boxes. The unaccounted portion of Al that was neither flushed nor retained represents dissolved Al in the effluent (3-4% of the total Al).

Changing to *TBF* mode complicates solids removal calculations because the system discharges water between flushes. The metals that leave in the effluent must be subtracted from the flushable solids total for an accurate accounting of solids removal.

In *TBF* mode the boxes were flushed for five minutes on Mondays and Fridays which released all but a few inches of water. The west box, whose limestone had not been cleaned, flushed 34% of the Al that entered the box. Between flushes an average of 15% of the Al was discharged with the system effluent, primarily as particulate Al. In total 40% of flushable Al solids were removed with 9% leaving the system in solution. This leaves 51% of Al retained within the system. A 49% Al removal rate from the coated stone of the West Box while producing net alkaline effluent is an accomplishment not duplicated in either the Jonathan Run systems or the Mitchell Tank. It is also an improvement over the 33% removal observed when the West Box was operated in *LBF* mode.

To assess the influence of flush duration on solids removal, the West Box was programmed to flush for two minutes every Monday and Friday which resulted in a drawdown of 1.8 feet. The flow rate of the flush is proportional to the head in the box and thus declines throughout the flush. As a result a two minute flush is 40% of a five minute flush duration, but releases 44% of the water volume of a five minute flush.

Figures N and O show an accounting of Al into and out of the system.

Figure N. Average Al flush, discharge and retention from the West Box for 5 minute flush duration.

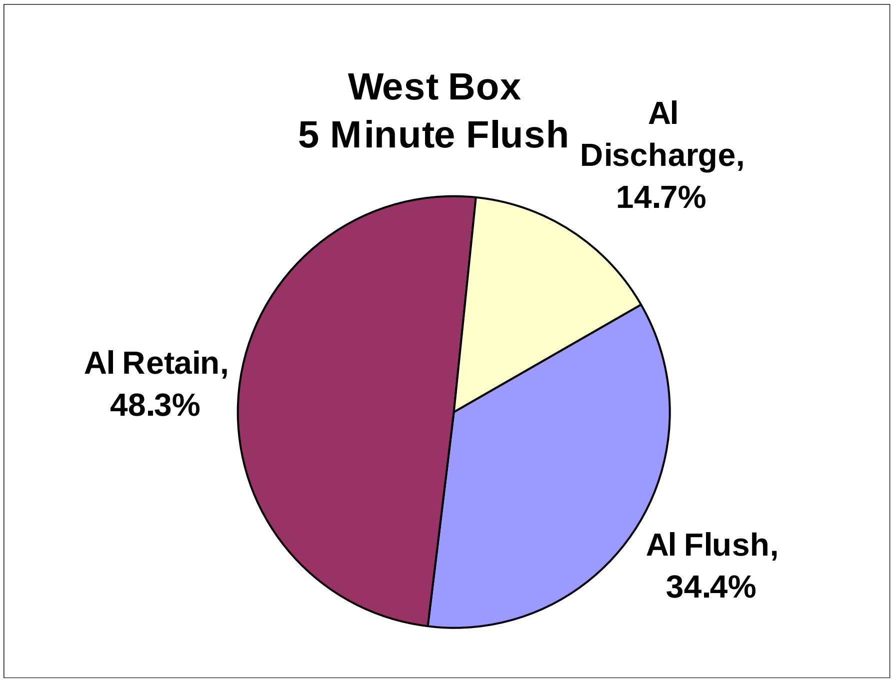
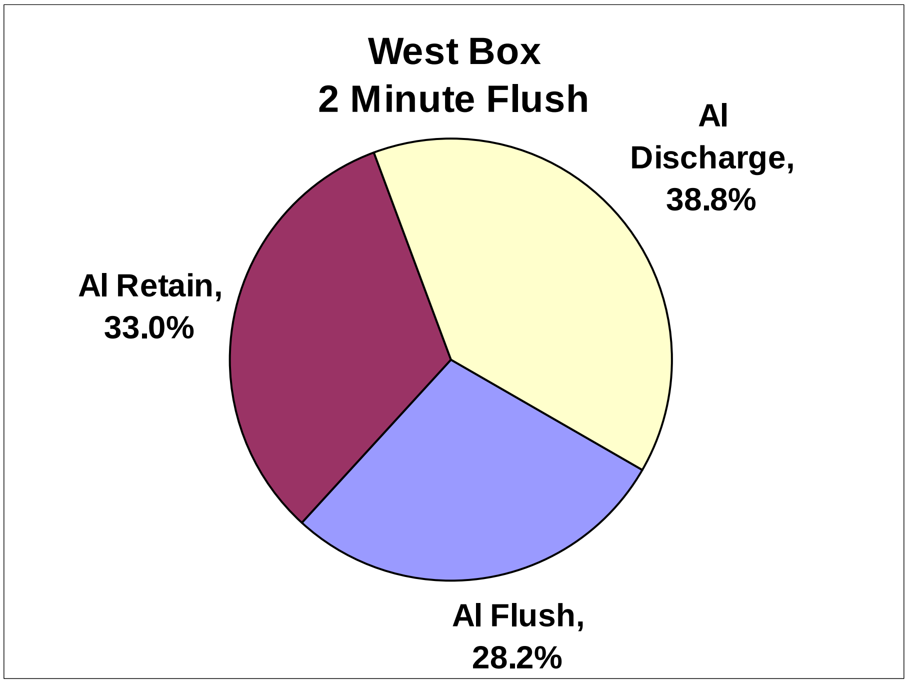
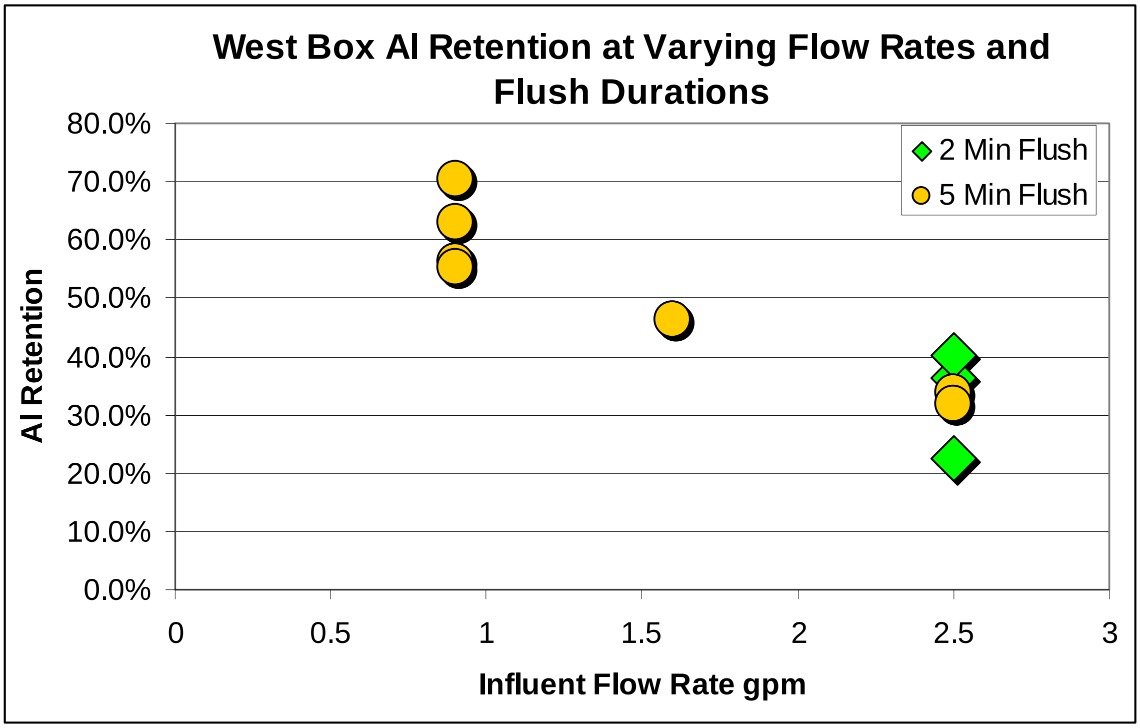


Figure O. Average Al flush, discharge and retention from the West Box for 2 minute flush duration.



At first blush the results seem to show that a five minute flush flushes more Al than a two minute flush. However when influent flow rate is taken into consideration it becomes clear that in *TBF* mode the amount of Al retained depends more on flow rate than flush duration. This is because at higher influent flow rates more Al is discharged between flushes reducing the amount of flushable solids that form within the box. Figure P plots Al retention against influent flow rate for both flush durations.

Figure P. West Box Al Retention at varying flow rates and flush durations



A comparison of flush performance at several flow rates and flush durations is shown in Table 14. Two samples collected when the West Box was not flushed are also included to represent the performance without flushing. The high influent flow rate of the un-flushed samples is sufficient to remove nearly one quarter of the Al.

Table 14. Al flushing assessment of the West Box

flow gpm	Flush Duration Minutes	n	Al Flushed	Al Discharged	Al Retained	FE*
5.5	0	2	0	24%	76%	NA
2.5	2	3	28%	39%	33%	43%
2.5	5	2	30%	37%	33%	48%
1.6	5	1	40%	14%	46%	46%
0.9	5	4	35%	4%	61%	11%

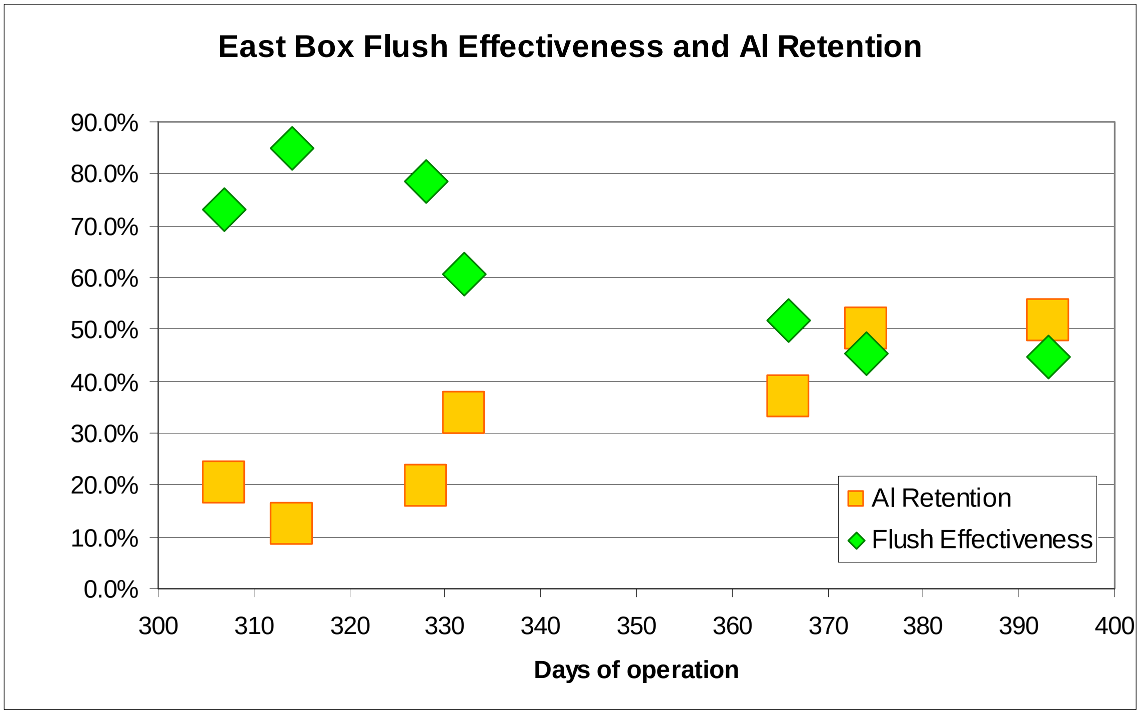
**FE - Flush Effectiveness which is the amount of flushable solids removed from the system. See section XX*

The proportion of aluminum removed by the flush remains relatively constant regardless of influent flow rate and flush duration. The amount of Al leaving the system between flushes appears to be the dominant factor that determines the flushing effectiveness. The proportion of Al leaving the system between flushes is directly related to influent flow rate.

The flushing effectiveness of the East Box was assessed following the cleaning of the limestone. The first sample of the flush was collected 49 days after the cleaning to avoid misleading results due to residual solids from the cleaning operation. The flow rate was 2.0 gpm.

The East Box averaged 32% Al retention. The retention was increasing over time from 20% at the first sample to 52% at the final sample where it appeared to stabilize. Flush effectiveness averaged 63% but was also declining, stabilizing around 45%. This is in line with the flushing effectiveness of the West Box at flow rates greater than one gpm (Table 14). Figure Q shows the flush effectiveness and Al retention over time.

Figure Q. Aluminum retention and flushing effectiveness for the East Box post-cleaning.



Note: The limestone in the East Box was cleaned on day 258

Iron Retention and Flushing

Iron removal by flushing was calculated using the same methodology as was followed for aluminum. Influent iron concentrations averaged 9.2 mg/L. With few exceptions dissolved Fe was less than 0.2 mg/L in both the effluent and the flush. As a result it was assumed that all influent Fe was precipitated within the system and no correction was made for dissolved Fe in the system effluent or flush. The West Box flushed 41% of influent Fe and the East Box flushed

63% of influent Fe. The amount of Fe flushed by the East Box was as high as 93% in the months immediately following the cleaning of the limestone but then declined to an average of 52% for October and November. Like with Al, Fe retention varied with iron concentrations in the effluent. The proportion of Fe flushed remained relatively constant while the remaining Fe was either discharged with the effluent or retained. Greater effluent Fe concentrations resulted in less Fe retained and lower effluent Fe concentrations resulted in more Fe retained. On average, the West Box retained 49% of Fe and the East Box retained 24%.

With an average influent Fe concentration of 9.2 mg/L, a flow rate of 0.9 gpm and an Fe retention rate of 49%, the system would retain 17.8 lbs of Fe per year. This mass of Fe will produce approximately 19 gallons of iron hydroxide sludge (15% solids, 10 lb/gal) per year that would be retained within the limestone. This represents less than one percent of the total void space in the system. Maintaining the Fe retention rate of 49% but quadrupling the influent iron concentration to 36.8 mg/L results in an annual retention of 71 lbs of Fe. This mass of Fe will produce approximately 81 gallons of iron hydroxide sludge. This represents less than 5% of the total void space in the system.

Cost Analyses

A cost analysis of the flush system was conducted. The analysis considered the costs to construct a self-flushing system and the costs to operate it for twenty years. The model system was based on the Mitchell tank, whose installation costs are known, with modifications developed from the results of this project. The system was assumed to treat the Mitchell discharge which has the following chemistry: pH 3.0, acidity 250 mg/L, Al 20-30 mg/L; Fe 1-10 mg/L; and Mn 10-20 mg/L. This AMD is similar to hundreds of discharges from unflooded abandoned deep mines in Pennsylvania.

The system parameters are shown in Table 15. The 100,000 gallon circular tank, made with reinforced concrete, was assumed to cost $30,000. The current 100,000 gallon Mitchell tank cost $25,800 (installed) in 2004. The system would be equipped with two AgriDrain 9” Smart Drainage units that would be custom built so that they operated off a single microprocessor and solar panel array. The tank would be filled with 750 tons of #5 Special 98% $CaCO_3$ aggregate which can be purchased and delivered to the Mitchell site (80 mile haul) for $18-20 per ton. The flush system would discharge to a 150,000 gallon settling pond. This pond capacity is four times the flush volume and will retain the average flow for 48 hours. This pond likely has enough storage to hold at least 10 years of solids. A contractor is assumed to conduct earthwork, fill the tank with limestone and complete the equipment installation for $15,000. Engineering input and oversight during construction is assumed to cost $10,000.

Table 15. Estimated cost to construct 100,000 gallon flush system

Item	**detail**	**Cost basis**	**cost**
Tank	100,000 gallon manure storage	Mitchell tank was $25,800 in 2004	$ 30,000
Limestone	750 tons 98% $CaCO_3$	$20/ton delivered (2008 cost)	$ 15,000
Flush device	Two 8 inch AgriDrain	Current cost estimate	$ 8,000
contractor	Earth work, flusher and pipe installation	estimate	$ 15,000
pond	150,000 gallon pond	Estimate	$ 15,000
plumbing	Miscellaneous	Estimate	$ 2,000
Engineer	Design and manage	Estimate	$ 10,000
total			**$ 95,000**

The construction costs for the flush system do not include discharge and site specific items that vary between projects. These items include: discharge collection, discharge conveyance, surveying, permitting, and access road development. These items generally cancel out when the costs of alternative technologies are being compared. AMD Treat calculates treatment costs separately from site-specific costs.

The Mitchell system provides a good example of site specific costs. The total installation costs for the system was approximately $160,000. This included two mine water collection systems, a 2,200 ft buried 10" diameter pipeline between the mine adits and limestone bed, a flow control box, and a 320 ft buried 18" diameter pipeline between the limestone bed and the settling pond. The design and installation of these features required a surveyed map and additional engineering. These items were necessary because the discharges were not located in an area suitable for treatment and because the local bedrock is a very hard sandstone that cannot be ripped.

The system's standard operational assumptions are shown in Table 16. The AMD loading is based on the results obtained from the East Box in the fall of 2008. At that time the box was operated at 2 gpm and an effluent that was consistently net alkaline with low metals was produced for five months (until the unit was dismantled). The limestone in the East Box during this period had been exposed to high loads of AMD for nine months and had been cleaned once. At 2 gpm the East Box's acidity loading rate was 0.19 lb acidity/day for each ton of limestone. At an average influent acidity of 250 mg/L and a tank capacity of 750 tons limestone, the flow rate for the modeled system is calculated as 47.5 gpm. The system is assumed to discharge water with -25 mg/L acidity. The system's limestone consumption is 29 tons/yr.

The system's routine operation is assumed to require regular inspections and occasional repairs of the automated flushing device. System inspections can be done by non-technical personnel. During the 18 month project, flush device repairs included the replacement of one battery and one actuator at a total cost of about $200. (Both were covered under warranty so there was no cost.) The cost model assumed that the total annual cost for inspections and equipment repairs was $1,500 per year.

The limestone must be cleaned periodically. The cost and frequency of the cleaning is an important component of the system's operation, so these parameters were varied to determine their significance to total long-term costs.

The settling pond must be clean out periodically. One cleanout in the 11th year where the sludge is pumped to a disposal basin and buried was assumed to cost $15,000

Table 16. Assumptions of Flush System operation

Item	Basis	Value
Acid loading	Lb acid/day per ton LS	0.19
Flow		47.5 gpm
Influent chemistry	Mitchell	pH 3.0, acid 250, Al 20-30, Fe 1-10
Effluent acidity		-25 mg/L
Lifetime of system		20 years
Routine operations	$/yr for inspections	$500
Routine maintenance	$/yr for flush repairs	$1,000
Settling Pond Cleanout	Per Event	$15,000
Settling Pond Cleanout	Frequency	Every 11 years
LS cleaning		
Unit cost	Variable	$2.50 - $7.50/ton LS cleaned
LS replacement	Replace dissolved LS	$20/ton
Frequency	Variable	1 to 3 years

The total treatment costs were related to the alkalinity produced by the system. The alkalinity was calculated from the difference in influent and effluent acidity (275 mg/L) and the design flow rate (47.5 gpm). The annual alkalinity generation was 29 tons $CaCO_3$. Construction and operational costs were summed over the 20 year period. The values were not discounted to make their comparison with other technologies simpler.

Table 17 shows the 20 year unit treatment costs at a variety of limestone cleaning costs and intervals. Limestone was cleaned in this project for as little as $2.50 per ton. This was accomplished by a contractor who had already cleaned stone twice and had developed an efficient simple washing technique. The cost for an inexperienced contractor will be higher.

The frequency of the limestone cleaning is estimated to be between 1 and 2 years. The same grade of limestone loaded at 2.75 times higher rate, was cleaned after 6 months of treatment in the East Box. This would suggest a 1.0 – 1.5 year cleaning frequency for the modeled system. However, the West Box was subjected to the same overloaded conditions and was never cleaned. At the end of the project (15 months of AMD treatment) it was producing a net alkaline discharge with at 1-2 gpm flows. This suggests that a 2-3 year frequency may be possible.

For comparative purposes, a one-year cleaning frequency at $3.75/ton was assumed. The unit cost under these conditions and the assumptions shown in Tables 15 and 16 is $359 per ton alkalinity. The unit per flow cost under the same conditions and assumptions if \$0.411 per thousand gallons.

Table 17. 20 year treatment costs, \$/ton $CaCO_3$ generated at varying cleaning frequencies and limestone cleaning costs.

	Cost to clean one ton limestone				**100% replacement**
Cycle (years)	**\$2.50**	**\$3.75**	**\$5.00**	**\$7.50**	**\$22.00**
0.5	411	474	537	663	1,168
1.0	328	**359**	391	454	706
1.5	300	321	342	384	552
2.0	286	302	318	349	475
2.5	278	291	303	328	429
3.0	272	283	293	314	399

Table 17 also shows unit costs for the highly conservative assumption that the limestone is always replaced. Based on the West Box findings, complete replacement of a properly managed system could be necessary every 2-3 years. The two-year interval has a unit treatment cost of \$475/ton $CaCO_3$.

Table 18 shows 20 year treatment costs for other AMD treatment technologies. Two entries for the self-flushing technology are provided. A base cost is provided that does not consider site-specific factors. A second “Mitchell” cost is provided that incorporates the actual Mitchell system installation costs (\$160,000). The least expensive effective acid-neutralizing technology is in-stream lime dosing. This method does not manage metals and uses the receiving stream for solids settling. The most common passive approach to acidic water containing Al is vertical flow ponds systems. The Anna S passive system, which is located adjacent to the Mitchell flush systems, treats AMD with vertical flow ponds and a settling pond. Five years of costs and performance are known. The discharge from the system has been continuously alkaline with low metals. Future replacement of the organic substrate in the VFPs is expected and included in the cost evaluations. The net cost is estimated at \$408/ton $CaCO_3$. AMD that does not contain Al is often suitable for treatment with ALD systems. These systems are reliable and cost-effective (Skousen and Ziemkiewicz, 2005). The SR-114D system is a very simple design that has the lowest unit treatment costs calculated to date. The LC20D system is a more complicated system that was located in a remote location next to a stream that required costly transportation of materials in and out of the project area. Its unit costs are substantially higher.

Table 18. 20 year treatment cost calculations for several AMD treatment technologies in PA. Costs are not discounted.

Technology	Treatment	\$/ton $CaCO_3$ (20 yr)	Source	Capital \$ basis[A]	O&M \$ basis[B]
Self flush	Acidity and metals	\$359	This project	Modeled	18 month projection
Self flush, Mitchell	Acidity and metals	\$473	This project	Actual	18 month projection
Lime doser	Only acidity	\$292	Ziemkiewicz[C]	Actual	Unknown 2 years?
VFP system	Acidity and metals	\$408	Anna S VFP system (HE)	Actual	5 year projection
ALD system	Acidity and metals	\$232	SR114-D (HE)	Actual	13 year projection
ALD system	Acidity and metals	\$537	LC20D (HE)	Actual	2 year projection
Lime system	Acidity and metals	\$875	BrandyCamp (BAMR)	Actual	5 year projection
NaOH	Acidity and metals	\$1,100	AMD Treat	modeled	Modeled
NaOH	Acidity and metals	\$2,464	Ziemkiewicz[C]	Actual	Unknown 5 years?

[A] *Actual* costs derived from project budgets; *Modeled* costs from Table 15 or AMDTreat

[B] period of time over which known O&M costs are known and used to project to future; modeled NaOH costs from AMDTreat

[C] from, Ziemkiewicz, P. 2007. Optimizing Resources for Restoring Streams Impaired by Acid Mine Drainage. West Virginia Water Research Institute. http://www.wvca.us/wvwn/powerpoint/optimizing_resources_restoring_streams_acid_mine_120307.ppt#419,1,

The conventional chemical treatment approach in Pennsylvania for remote low-flow AMD seeps is NaOH addition. Ziemkiewicz reports unit costs of NaOH treatment for small seeps as \$ 2,464 per ton $CaCO_3$. This cost, which includes sludge management, seems unreasonably high. AMD Treat was used to estimate the costs to treat the same flow and chemistry used estimate flush system costs (Table 16). The cost of NaOH alone is \$550/ton $CaCO_3$ (20% NaOH at \$0.60/gallon delivered). Assuming that capital costs (tanks, metering equipment and ponds) are \$25,000 and that the system requires 10 hr/wk of manpower (\$25/hr), then a unit cost of \$1,100/ton $CaCO_3$ is estimated.

A less expensive chemical alternative for large flows is lime and polymer addition. The Brandy Camp plant treats acidic drainage containing Al and Fe using lime, polymer, electrical pumps and motors, and a sludge dewatering system. The plant's final discharge is reported to be alkaline with very low metals. The unit cost of the system (capital plus annual costs over 20 years) is reported by BAMR to be \$875/ton (D. Sammarco, personal communication).

Summary Discussion

The effectiveness of limestone aggregate as a source of alkalinity in the passive treatment of acid mine drainage depends on the ability of the stone to remain reactive and the limestone bed to remain permeable. Without reactivity, acidic water that contacts the limestone surface will not benefit from neutralization or alkalinity generation. Without permeability, acidic water will not be able to flow to the reactive surfaces. Advances during the last 15 years in the treatment of AMD with limestone aggregate have generally emphasized the control of permeability-affecting processes because of the numerous limestone beds that have failed due to plugging with metal solids. The most common plugging problem has been aluminum and the most commonly used anti-plugging action has been the flushing of limestone beds so that solids are removed and permeability maintained.

This project utilized high velocity, rapid drawdown flushing systems in an effort to maintain limestone reactivity and aggregate permeability even when exposed to high loads of acidic water with aluminum. The characteristics of the AMD and the treatment flush systems are shown in Tables 19 and 20.

All five limestone beds were exposed to AMD concentrations and loadings much higher than is considered suitable for passive treatment systems. The authors have observed anoxic limestone drains that failed due to plugging with Al solids at concentrations greater than 3 mg/L. BAMR's Treatability guidance indicates that AMD with more than 5 mg/L is unsuitable for passive treatment (Cavazza et al. 2008). Both flows of AMD utilized in this project had Al concentrations at least 20 mg/L. VFPs are routinely sized based on acidity removal expectations. Several studies suggest that the acidity removal limits for properly designed and constructed VFPs are 30-40 g m^{-2} day^{-1}. The limestone systems in this study received at least 85 g m^{-2} day^{-1}acidity and were tested at loads as high as 475 g m^{-2} day^{-1}. Rose (2002) suggests that Al loading rates to VFPs should be less than 4 g m^{-2} day^{-1} to avoid plugging problems. The Al loadings to the flush systems routinely exceeded 20 g m^{-2} day^{-1}.

Table 19. Average influent chemistry and system loadings for the three systems.

	Jonathan boxes	Mitchell tank	Mitchell boxes
Influent Chemistry			
Al, mg/L	45	27	27
Mn, mg/L	8	15	15
Fe, mg/L	1	8	8
pH	3.5	3.0	3.0
Acidity, mg/L	282	226	226
Loadings			
Flow, gpm	2	50	2
Acidity, g m^{-2} day^{-1}	197	331	158
Acidity, (lb/d)/ton LS	0.194	0.22	0.170
Al, g m^{-2} day^{-1}	45	40	19
Al, (lb/d)/ton LS	0.031	0.03	0.020

Table 20. Construction characteristics of the flush systems.

	Jonathan Run	**Mitchell Tank**	**Mitchell Boxes**
Construction Date	May 2003	December 2005	October 2007
Construction Type	6,060 gallon roll off container	117,000 gallon concrete tank	6,060 gallon roll off container
Limestone Mass	35 Tons	625 Tons	32 Tons
Limestone Size	AASHTO #1 and #3	AASHTO #1	AASHTO #5 special
Bed surface area	159 ft^2	2002 ft^2	159 ft^2
Bed thickness	5.0 ft	6.0 ft	4.5 ft
Flush Type	Fluid Dynamic Siphon, 8 inch, Model 0860	Fluid Dynamic Siphon, 14 inch, Model 14108	AgriDrain Smart Drainage System (8 inch diameter)
Ave Flush Rate	700 gpm	2,500 gpm	400 gpm
Drawdown Rate	1.3 feet/minute	0.4 feet/minute	0.7 feet/minute
Flush duration	3.5 minutes	15.5 minutes	5.0 minutes
Drawdown extent	Complete	Complete	Complete

Aggregate permeability

None of the limestone beds displayed permeability or plugging problems that interfered with their filling and flushing. The flush systems and their operation differ in several important manners from the flush systems in vertical flow ponds (VFPs). First, the flush drawdown rates of 0.4 – 1.3 ft/min are at least two orders of magnitude faster than drawdown rates for VFPs. Second, all of the systems were completely drawn down during flushing which drained all of the pores in the limestone bed. VFPs are rarely drained down more than several inches and the pore space within the limestone is typically not emptied.

Effluent Quality

The flush systems were capable of producing high quality effluents. The ability of clean limestone to temporarily produce alkaline water with low metals is well known. But within weeks or months of exposure to AMD, the limestone reactivity usually decreases enough to cause a degraded effluent. This project showed that a flushed bed of limestone was capable of producing a quality effluent for at least a year. The ability of a limestone bed to produce a quality effluent was dependent on loading rates. At low loading rates, effluents potentially compliant with all metals contained in a standard NPDES permits were produced. Table 21 shows the effluent chemistry for the West Mitchell box when it was operated at 0.9 gpm for several months. This experiment occurred late in the project after the limestone had been continuously exposed for one year to much higher loads of AMD. The limestone in the West box was never cleaned. At an acidity loading rate of 90 g m^{-2} day^{-1}, the unit was still capable of producing a net alkaline discharge with low metals. As the effluent from the box flowed into a settling pond, the final discharge metal concentrations were lower than shown in Table 21.

Table 21. Effluent chemistry for the West Box between October and December 2008. All metals are total concentrations. Flow on all dates was 0.9 gpm. The unit was operating in TBF mode.

Date	**Acid load g m^{-2} day^{-1}**	**pH**	**Acid mg/L**	**Fe mg/L**	**Al mg/L**	**Mn mg/L**
Avg. Influent	89	2.93	270	11.4	30.8	18.1
Effluent 10/13	90	6.52	-67	0.5	1.2	1.5
Effluent 11/16	87	6.76	-69	0.8	1.6	2.8
Effluent 10/24	90	6.70	-87	0.3	0.7	1.0
Effluent 11/12	90	6.58	-46	0.4	0.8	1.5
Effluent 12/8	87	6.62	-38	1.0	3.2	3.7
Avg. Effluent		6.64	-61	0.6	1.5	2.1

The effluent data shown in Table 21 would satisfy the terms of most coal mine drainage NPDES permits. A typical permit requires the following effluent conditions

- pH: 6-9
- Fe: less than 3 mg/L monthly average; less than 6 mg/L monthly maximum
- Mn: less than 2 mg/L monthly average; less than 4 mg/L monthly maximum

The West Box produced an effluent compliant with these terms between October and December 2008.

The removal of Mn is not a primary objective of most AML projects. More typically, the treatment objective is a net alkaline effluent with pH >6 and with Al and Fe less than 3 mg/L. These effluent targets were achieved at a higher loading rate. Table 22 shows the effluent chemistry of the East box between August and November 2008. The effluent was consistently alkaline with low metals. When metals were measured, they were found to be largely suspended solids which readily settle in the settling pond.

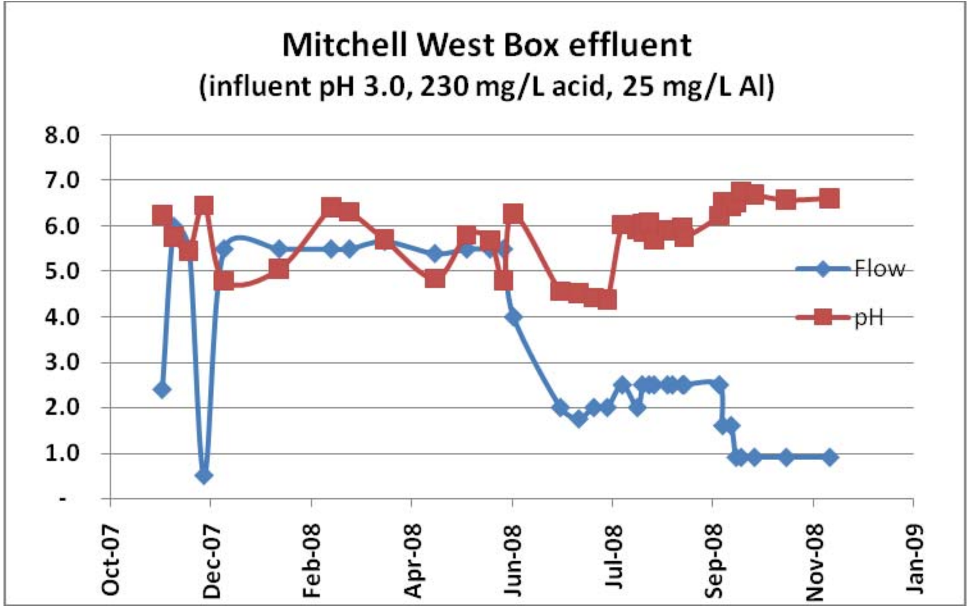
Table 22. Effluent chemistry for the East Box between August and November 2008. All metals are total concentrations. Flow on all dates was 1.9 – 2.0 gpm. The unit was operating in *flood&flush* mode.

Date	**Acid load g m^{-2} day^{-1}**	**pH**	**Acid mg/L**	**Fe mg/L**	**Al mg/L**	**Mn mg/L**
Avg. Influent	*175*	*2.9*	*251*	*10.6*	*28.0*	*16.9*
Aug 25	156	6.5	-42	1.6*	3.9*	5.6
Sept 2	163	6.8	-62	0.5	1.1	1.1
Sept 8	170	6.8	-60	0.9	3.0	2.3
Sept 28	175	6.3	-20	1.6*	7.1*	7.0
Oct 3	173	6.8	-74	1.0*	1.9*	2.6
Oct 5	175	6.9	-79	0.7*	1.3*	2.0
Oct 16	185	6.3	-24	1.7*	6.7*	6.9
Oct 24	190	6.6	-99	1.2*	2.7*	3.1
Nov 12	191	6.7	-70	1.4	2.1	3.4

** dissolved concentration was <0.5 mg/L*

The Mitchell West Box was subjected to a variety of experiments that involved overloading, changes to flushing modes, and changes to the influent plumbing. The limestone was never cleaned or disturbed. Figure R shows the effluent pH during the entire 419 day experimental period included in this project. The unit produced a highly improved effluent continuously and an NPDES-quality effluent when the flows were maintained at ~1 gpm. The West Box is currently being maintained by the BCWA. As of January 15, 2009 (457 days into the experiment), the effluent was still net alkaline with pH 6.5.

Figure R. Influent flow rate and effluent pH for the Mitchell West Box.



The loading rates successfully treated at the end of the project, 87 – 191 g m^{-2} day^{-1}, are very high relative to other passive treatment technologies. Effective VFPs are usually sized at 30-40 g m^{-2} day^{-1}. Thus the flush units were 3-5 times more land-efficient. Both passive systems should be followed by ponds to settle solids. VFPs do not affect Mn and its removal requires additional ponds or wetlands that can easily double the system footprint. The same alkaline low-Mn effluent shown by Table 21 would require about 3 times more land area if a passive VFP approach was utilized.

The generation of alkaline water with low metals from a limestone bed cannot be sustained indefinitely. The Jonathan units were loaded with 197 g m^{-2} day^{-1} of acidity and after three years of abandonment (with continual flushing), the treatment performance had decreased to 18% of the original performance. The Mitchell tank was loaded with 331 g m^{-2} day^{-1} of acidity. After two years, it performance had declined to 27% of the original performance. When limestone beds are severely overloaded, their alkalinity generating performance decreases to about 20% of that seen when the limestone is clean. Inspection of these fouled limestone beds revealed that most exposed limestone surfaces were covered with a hard scale that obviously lessened the ability of acid water diffuse to the calcite surface and for alkaline dissolution products to diffuse away from the calcite surface.

Given the extent of the scale, it is surprising that any benefit is achieved with these fouled limestone beds. Yet, the systems continue to generate alkalinity. The relative reactivity, between 18-27% of the original reactivity, is similar to the 20% value reported by Ziemchevicz (1997) for armored limestone in oxic limestone channels (OLC). An OLC is only intended for steep slopes that provide flow velocities necessary to wash away solids and keep the limestone aggregate permeable. (On shallow slopes limestone-filled channels fill with metal solids and the AMD does not contact the calcite.) A high velocity flush system that is overloaded and not maintained appears capable of producing the same performance as an OLC, without steep slopes.

Aggregate Size

Alkalinity generation by limestone in flush systems was affected by aggregate size. Smaller aggregate, which has more surface area per ton, generates alkalinity faster than larger aggregate. Three aggregate sizes were utilized in this project: AASHTO #1, AASHTO #3, and gradation similar to AASHTO #5 that is produced for use in fluidized bed coal combustion plants. Table 23 shows the size breakdown for the aggregates. The table also includes a surface area approximation.

The particle size affect was maintained with loss of alkalinity generating capacity. At the Jonathan site, AASHTO #3 aggregate, which out-performed AASHTO #1 aggregate when the limestone was clean, maintained a 30% treatment advantage three years later when the stone was scaled.

Table 23. Size and grading requirements for coarse aggregates

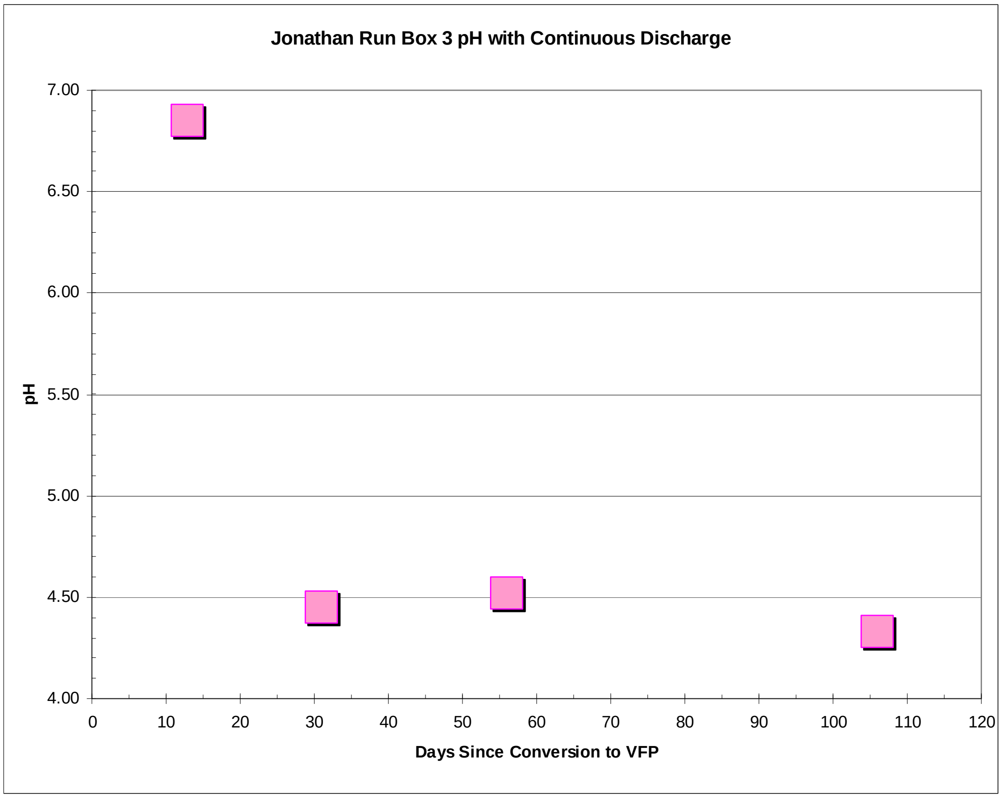
	Total Percent Passing								**SA***
	4”	**3 ½”**	**2 ½”**	**2”**	**1 ½”**	**1”**	**¾”**	**½”**	**ft^2/ton**
AASHTO #1	100	90-100	25-60		0-15		0-5		400
AASHTO #3			100	90-100	35-70	0-15		0-5	670
AASHTO #5					100	90-100	20-55	0-10	1,200

** surface area of stone estimated from stone size fractionation and generalized shape assumptions*

Flush Benefits

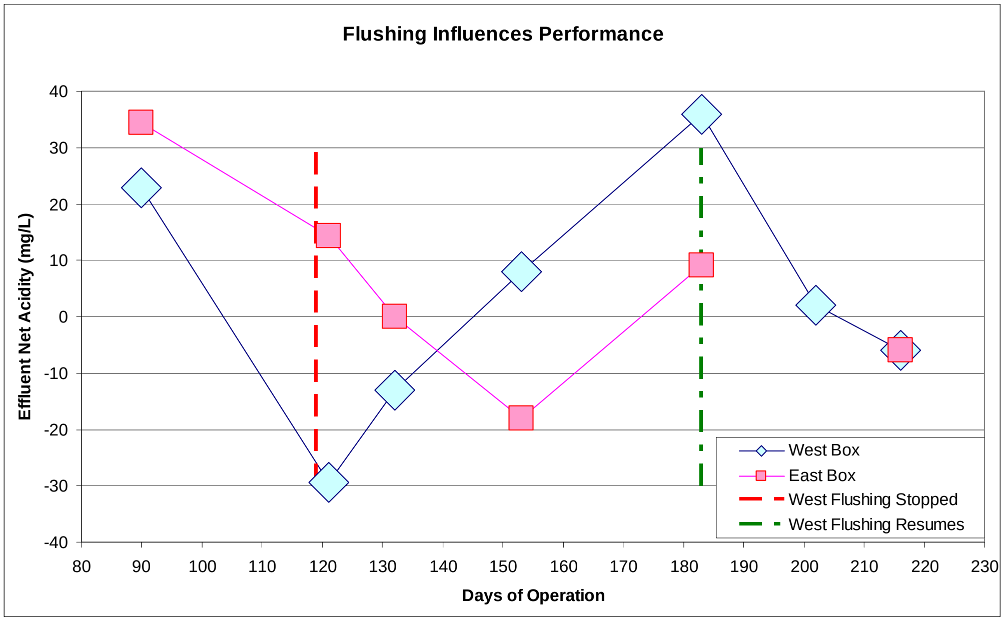
The benefit of flushing a limestone bed that is being used to treat AMD was demonstrated by accidental and intentional experiments. After the limestone in Box 3 at the Jonathan system was cleaned, damage to the container caused the flushing mechanism to fail and the system operated as a flooded limestone bed continuously for several weeks. Initially the quality of the discharge improved dramatically. After several weeks the accumulation of Al solids at the top of the bed became visibly conspicuous and the quality of the effluent declined greatly (Figure S). At the time it was unclear whether the initial improvement in performance was due to the cleaning of the limestone or the change in flow pattern. Subsequent experiments at the Mitchell Site demonstrated that the change in flow pattern was largely responsible for the improved performance. During the same period the adjacent Box 1, which flushed continuously, provided consistent water treatment.

Figure S. Effluent pH of Jonathan Run Box 3 with continuous discharge and no flushing



A similar result was obtained intentionally from the Mitchell boxes when the West box was operated for 64 days without flushing (Figure T). The box was fully flooded during the period. Initially, the effluent from the bed was better quality (more negative acidity) than was obtained through regular flushing. Within a week, the quality of the discharged began to degrade and eventually become net acidic. When flushing was resumed, treatment effectiveness was reestablished.

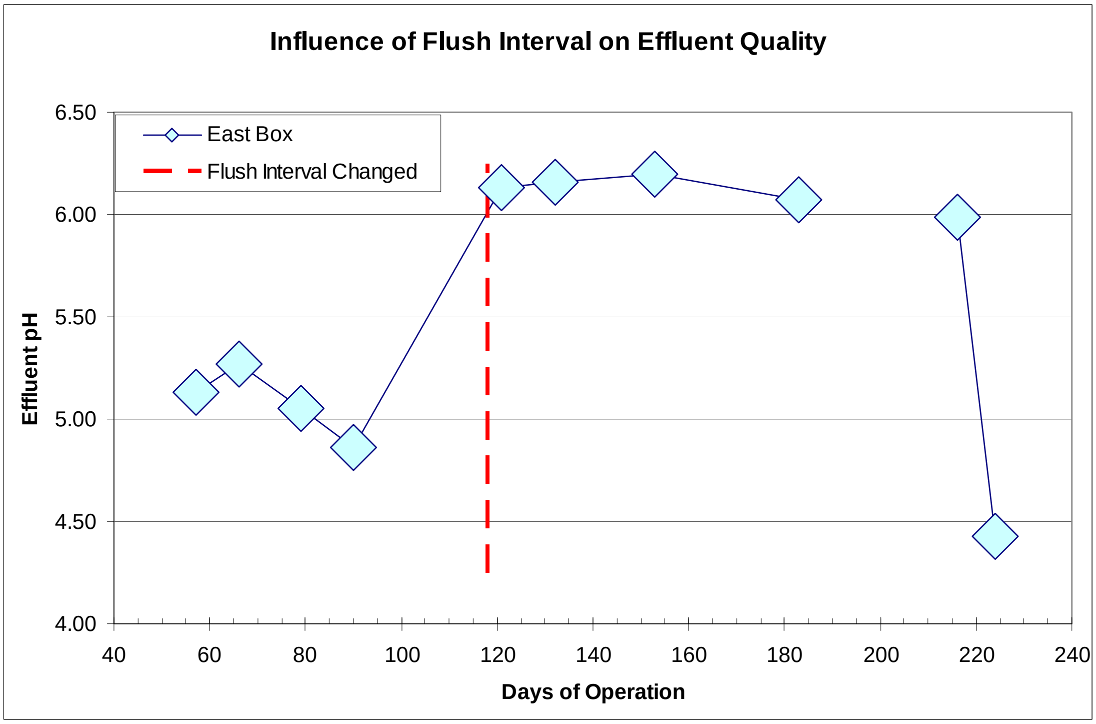
Figure T. Comparison of the effluent net acidity when the Mitchell boxes were operated in different flushing modes. (negative values indicate better treatment)



Flood & Flush Mode

The short-term generation of good effluent from a flooded bed of limestone was not surprising as this is a common result of contact between AMD and clean limestone. The challenge is to maintain the limestone in a condition that allows the treatment effectiveness to be sustained over an extended period. Periodic high velocity flushing can provide the necessary conditioning of the limestone. The Mitchell East box was set up to run in a flooded mode with high velocity flushing twice a week (time based flush mode, TBF). The TBF mode produced a continuous low flow effluent during flood mode, and a short term high flow effluent during flush events. The system was operated in this mode for 298 days (until the end of project). Figure z shows chemical and flow conditions during the period when the flush was changed from LBF to TBF. The flood & flush mode resulted in better effluent chemistry under similar loading conditions.

Figure U. Effect on effluent pH of shifting from a flushing system based on water level (LBF) to one based on time (TBF).



Solids Removal through Flushing

The flush systems commonly produced highly turbid flushates. The solids content of the flushates was assessed by analyzing samples for total and dissolved metals. The difference of total (X^{tot}) and dissolved (X^{dis}) measurements was the calculated solid concentration (X^{solid}). The amount of solids produced by flow through a unit was determined from the change in total metal concentrations,

$$\text{X-solids (mg/L)} = \text{X-in}^{tot} - \text{X-out}^{tot},$$

where X is Fe, Al, and Mn.

The flush efficiency (FE) is the proportion of solids formed that is contained in the flush. In the fill & flush mode, where discharge is only produced during flushes, the FE can be calculated from metal concentration measurements.

$$\text{FE} = \text{X-out}^{solid} / \text{X-solids}$$

The best performance in a LBF mode is transformation of 100% of the influent metal to a solid form that is completely flushed. This condition occurs when $\text{X-in}^{tot} = \text{X-out}^{solid}$.

For a TBF mode, the calculation is complicated by the accumulation of solids that occurs during operation in flooded mode. When the system is flushed, the removal of these solids can result in effluent solids concentrations larger than the influent. The flush efficiency is calculated as the mass of solids removed during the flush compared to the mass of solids accumulated during flooded operations.

$$FE = (\text{flush gallons} * X\text{-out}^{solid}) \ / \ (\text{flood gallons} * (X\text{-in}^{tot} - X\text{-out}^{tot}))$$

Where *flush gallons* were measured using a timed refill of the system at a constant flow rate and *flood gallons* were estimated from the flow rate and time period between flush events.

The relevance of FE depends on the limestone bed's transformation of dissolved metals to solids. This transformation was related to the pH of the bed effluent. When the effluent pH was > 6, a large portion of the Al and Fe solids were transformed to solids and the ability of the flushing action to remove those solids was an important component of the system's overall effectiveness. When the effluent pH was < 4, less transformation of Al and Fe to solids occurred and the ability of the system to efficiently flush a large proportion of those solids was not relevant to the system's overall treatment effectiveness.

The ideal operational condition of a system would be an effluent with pH >6 and dissolved metals < 1 mg/L and FE of 100%. Table 24 shows solids removal calculations for system units when they ran in a constant mode for at least two months. The West Box showed the same FE regardless of flush mode. However, during the 5.5 gpm data collection period the West Box had not yet reached the end of the "honeymoon" period so the importance of this comparison should be considered with caution. What's more, the West Box was producing higher quality effluent during the 0.9 gpm data collection period than during the 5.5 gpm period. The west box limestone was never cleaned. The East box limestone was cleaned on day 258. Following the cleaning FE unexpectedly surpassed 70% for 70 days after which the FE declined to ~45% where it appeared to stabilize. It is likely that the apparent stabilization is actually a transition to a more gradual decline and FE will eventually match the FE of the West Box at 37%.

Table 24. Flush Efficiency of the flush systems.

Unit	Mode	Flow	Effluent pH	Period	FE %
East Box	LBF	5.5 gpm	>5	Day 1-79	32%
West Box	LBF	5.5 gpm	>5	Day 1-79	37%
East Box	TBF	2.0 gpm	6.1+	Day 258-419	63%
West Box	TBF	0.9 gpm	6.1+	Day 363-419	37%

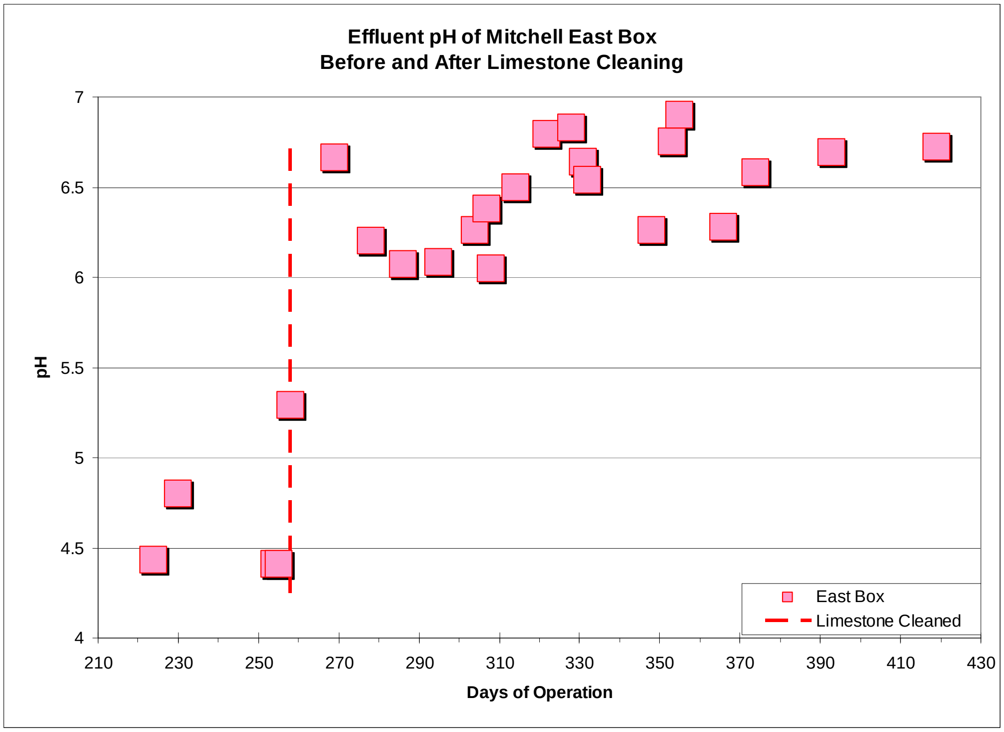
Iron removal by flushing was calculated using the same methodology as was followed for aluminum. Influent iron concentrations averaged 9.2 mg/L. With few exceptions dissolved Fe was less than 0.2 mg/L in both the effluent and the flush. As a result it was assumed that all influent Fe was precipitated within the system and no correction needed to be made for dissolved Fe in the system effluent or flush. The West Box flushed 41% of influent Fe and the East Box flushed 63% of influent Fe. The amount of Fe flushed by the East Box was as high as 93% in the months immediately following the cleaning of the limestone but then declined to an average of 52% for October and November. Like with Al, Fe retention varied with iron concentrations in the effluent. The proportion of Fe flushed remained relatively constant while the remaining Fe was either discharged with the effluent or retained. Greater effluent Fe concentrations resulted in less Fe retained and lower effluent Fe concentrations resulted in more Fe retained. On average, the West Box retained 49% of Fe and the East Box retained 24%.

Solids Removal through Limestone Cleaning

Solids not removed by flushing accumulate in the limestone bed and eventually cause its treatment effectiveness to degrade. The degradation is not due to the loss of permeability, because the flushing actions maintained very high porosity in all of the limestone beds. The degradation is due to the accumulation of metals solids in the bed which lessens the ability of mine water to contact calcite surfaces. The excavation of several beds revealed two types of solids accumulation. Some of voids within the aggregate were filled with a wet *sludge* that was water with very high total suspended solids (Photo 31). This liquid appeared to be readily flushed from the system. It was not adhered to the limestone aggregate and when the stone was moved, it washed away. The second solids accumulation was scale onto the limestone surfaces that was adhesive enough to allow its inspection on stones removed from the bed. The scales were easily dislodged from the stones with mild mechanical abrasion (Photos 17 and 30). After the scales were removed, the limestone pieces appeared visually to be similar to fresh limestone (Photos 23 and 28).

Both sludge and scale can be washed off the aggregate, rejuvenating the stone and bed’s ability to generate alkalinity. Figure AA shows the pH of the effluent from the East Box before and after the limestone was cleaned. This improvement in effluent quality was observed after every limestone cleaning.

Figure V. Effluent pH of the East Box before and after limestone cleaning



Limestone aggregate was washed five times during the project. Each time, the washing process was simplified in an effort to lessen cost. The first cleaning included a pumped flow of clean water to wash the stone and carry the dislodged solids out of the system (Photo 18). Subsequent cleanings made use of the existing flow of mine water without a pump. Sludge and scale were readily removed when the aggregate was agitated in a pool or stream of water. The Mitchell tank limestone was washed by creating a pool within the tank. The East box limestone was washed in a stone box placed next to the roll-off container that had a continuous flow of mine water (Photos 26 and 27).

The solids exposed and released by cleaning activities were sampled and analyzed for elemental composition. The solids were a diverse mixture of metals. Table 25 shows the composition of several samples. The dominance of Al, Fe, and Ca minerals was expected from the mine water and the limestone. The dominance of Si was unexpected. Its source is probably the insoluble siliceous impurities in the limestone that become incorporated into Al and Fe solids that precipitate onto the calcite surfaces. It is also possible that Si contained in the AMD is precipitating in these alkaline environments, but this hypothesis could not be evaluated in this study. The solids are too impure to have any known or speculative value and will likely need to be disposed of.

Table 25. Composition of solids collected from limestone beds during excavation

	Fe_2O_3	**Al_2O_3**	**MnO**	**SiO_2**	**CaO**	**MgO**	**K_2O**	**S**	**LOI**	**Total**
	%	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
Jonathan Inlet	2.2	19.6	1.0	29.7	14.3	1.6	1.2	1.5	25.5	95.5
Jonathan Surface	1.6	36.9	3.5	16.9	2.3	0.5	0.5	2.8	36.0	98.6
Jonathan Mid	1.2	43.6	0.8	11.0	1.4	0.3	0.3	5.1	39.8	98.5
Jonathan Bottom	2.3	29.3	0.5	14.2	11.6	0.8	0.6	3.4	33.1	92.6
Mitchell-A	1.2	8.3	0.4	18.9	31.0	0.7	1.1	0.1	34.4	96.6
Mitchell-B	2.2	9.4	0.2	22.5	29.4	0.7	1.2	0.2	29.3	95.6
Mitchell-C	10.2	25.4	0.8	23.5	6.8	0.4	1.3	2.4	29.8	99.0
Mitchell-D	4.5	21.9	2.5	20.4	12.1	0.6	1.0	1.4	31.8	95.3
Mitchell Box East	8.0	29.1	1.5	20.2	6.2	0.5	0.7	1.7	30.8	97.4

Treatment System Design Implications

The project has established that limestone aggregate can be used for the effective treatment of low-pH AMD contaminated with Al, Fe, and Mn. Regular rapid flushing that completely drains the limestone bed was found to maintain the bed's permeability and eliminate problems associated with solids plugging.

Flushing as soon as the bed fills sacrifices treatment effectiveness because the contact time between mine water and the limestone is only half the theoretical maximum. Operating the bed in a flooded mode without flushing provides a short-term treatment benefit, but the quality of the effluent degrades significantly within weeks to months. A hybrid approach was developed that utilized flooded conditions with complete rapid flushing every 3-4 days. This approach was able to produce the best sustainable treatment. At a moderate loading level, the TBF mode was able to produce an alkaline effluent with low Al, Fe and Mn for three months. The effluent would have satisfied a typical NPDES permit. At a higher loading level, the TBF mode was able to produce a net alkaline discharge and low Al and Fe for at least six months.

Both the LBF and TBF modes produced alkaline low-metal effluents at loading rates far higher than are currently considered appropriate for vertical flow ponds. Effective VFP systems are generally loaded with 30-40 g m^{-2} day^{-1} of acidity. The boxes initially produced a circum-neutral effluent for five months when loaded at 425 g m-2 day-1ay of acidity. When the loading to the west box was decreased to 90 g m^{-2} day^{-1}, it produced a high quality discharge for the last three months of the project. The limestone in the west box was never washed. It is reasonable to expect that the TBF mode could treat 190 g m^{-2} day^{-1} of Mitchell-type AMD (pH 3.0, 20-30 mg/L Al) to a quality suitable for AML projects (net alkaline, low Al and Fe) for 1-2 years before limestone cleaning would be required to maintain effluent quality.

An economic analysis of the flush system indicated that the cost of the technology is quite competitive with alternative methods for treating highly acidic AMD. Projections of treatment costs for the TBF mode at a 190 g m^{-2} day^{-1} acidity loading summed in a 20 year analysis to $359/ton alkalinity generated. This cost is 23% higher than lime dosing, which involves the direct addition of lime to streams without any solids management. The cost is 15% lower than VFP approaches and substantially lower than conventional caustic and lime treatment.

Literature Cited

American Public Health Association (1999) Standard methods for the examination of water and wastewater. American Public Health Association, American Water Works Association, and the Water Environment Federation, 20th edn. Washington DC.

Cavazza, E., Sammarco, D., Milavec, P., Wood, T., Helfrich, D. and B. Means. 2008. Mine Drainage Treatability and Project Selection Guidelines. Published by the PADEP Bureau of Abandoned Mine Reclamation and the Office of Surface Mining Reclamation and Enforcement, Harrisburg, PA. 42 p.

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

Hedin RS, Watzlaf GR, Nairn RW. (1994b). Passive treatment of acid mine drainage with limestone. J Environ Qual 23(6):1338-1345

Kantz, Boyer, and Associates. 1976. Operation Scarlift, Babb Creek mine drainage abatement project: Pennsylvania Department of Environmental Resources, Scarlift Report, 125 p.

Kepler, A.A., and E.C. McCleary. 1994. Successive alkalinity-producing systems (VFW) for the treatment of acidic mine drainage. P. 195-204. In: Proceedings, International Land Reclamation and Mine Drainage Conference, April 24-29, 1994, USDI, Bureau of Mines SP 06A-94. Pittsburgh, PA

Pearson, F.H., and A.J. McDonnell. 1975. Use of crushed limestone to neutralize acid wastes. No. EE1, Proc. Paper 11131. J. Environ. Eng. Div., Am. Soc. Civil Eng. 101:139-158.

Reed, L.A. 1980. Effects of strip mining the abandoned deep Anna S mine on the hydrology of Babb Creek, Tioga County, Pennsylvania. U.S. Geological Survey Water-Resources Investigations 80-53. 41 p.

Rose, A. W., Bisko, D; Daniel, A; Bower, MA. 2004. An “autopsy” of the failed Tangascootack #1 vertical flow pond. *In:* 2004 Proceedings of the National Meeting of the American Society of Mining and Reclamation and The 25th West Virginia Surface Mine Drainage Task Force, April 18 – 24, 2004. ASMR, Lexington, KY

Rose, Arthur W. 2002. Performance of vertical flow systems for passive treatment of acid mine drainage. P. 809-815. *In:* Proceedings of the 6th International Conference on Acid Rock drainage (ICARD), July 14-17, 2003, Cairns, Australia

Skousen, J. and P Ziemkiewicz. 2005. Performance of 116 passive treatment systems for acid mine drainage. In: Proceedings of the 2005 National Meeting of the American Society of Surface Mining and Reclamation, Breckenridge, CO, June 19-23 2005. pp 110 -1131.

Turner, D., and McCoy D. 1990. Anoxic alkaline drain treatment system, a low cost acid mine drainage treatment alternative. In: Proceedings, 1990 National Symposium on Mining, University of Kentucky, Lexington, KY.

Weaver, K. , Lagnese, K., and Hedin, R. 2004. Technology and design advances in passive treatment system flushing. *In:* Proceedings, 2004 National Meeting of the American Society of Mining and Reclamation and The 25th West Virginia Surface Mine Drainage Task Force, April 18 – 24, 2004. ASMR, Lexington, KY.

Ziemkeiwicz, P.F., J.G. Skousen, D.L. Brant, P.L. Sterner, and R.J. Lovett. 1997. Acid mine drainage treatment with armored limestone in open limestone channels. J. Environ. Qual. 26:560-569.

Ziemkiewicz, P. 2007. Optimizing Resources for Restoring Streams Impaired by Acid Mine Drainage. West Virginia Water Research Institute. http://www.wvca.us/wvwn/powerpoint/optimizing_resources_restoring_streams_acid_mine_120307.ppt#419,1,

PHOTOS

Photo 1. Jonathan Run systems before insulation was installed. The roll off container on the right is Box 1 and Box 3 is on the left. The siphon vaults are visible to the right of the roll off containers.

Photo 2. Settling pond that receives effluent from the Jonathan Run systems.

Photo 3. Mitchell Tank under construction with underdrain plumbing exposed.

Photo 4. Completed Mitchell Tank. Siphon vault is visible in the background.

Photo 5. Mitchell Tank flushing into energy dissipater.

Photo 6. Energy dissipater discharging into settling pond during Mitchell Tank flush.

Photo 7. Mitchell Roll Off systems under construction. The West Box is in the foreground with the East Box behind. The 8” valves and Agri Drain smart drainage systems have been installed.

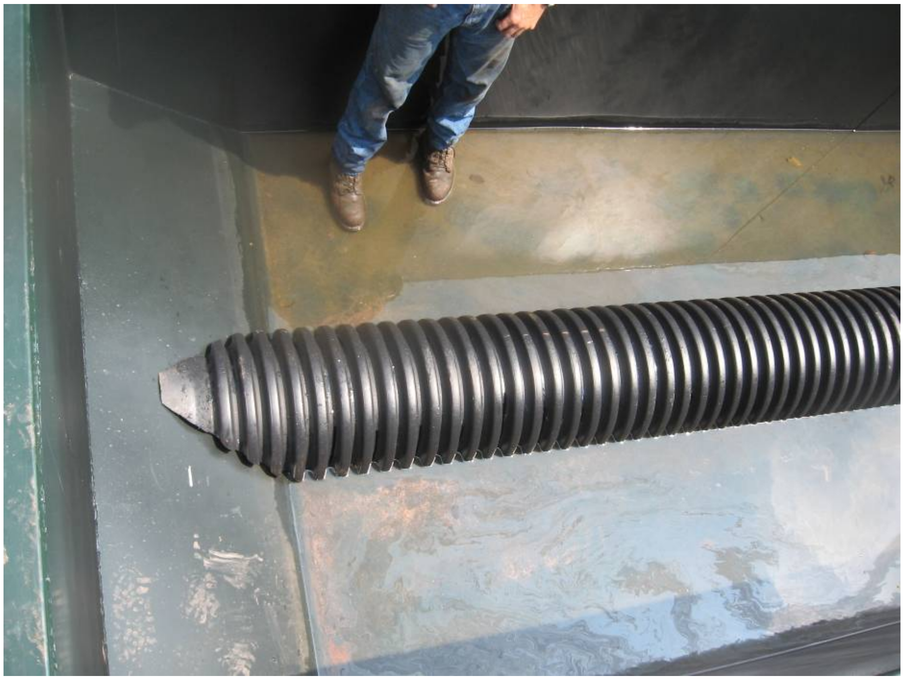


Photo 8. Mitchell Roll Off systems under construction. The underdrain plumbing consists of an 18” HDPE corrugated half-pipe that had been slotted with a chainsaw.

Photo 9. Aggregate used in Mitchell Roll Off systems.

Photo 10. Completed Mitchell Roll Off systems fitted with insulation.

Photo 11. Jon01 box before excavation. Its performance had declined by 75%.

Photo 12. Excavator starting to reveal contents of Jon01 box.

Photo 13. White stone on the surface of the Jon01 box.

Photo 14. Stone 12 inches below the surface was coated with yellow solids.

Photo 15. Coated rock at 24 inch depth in Jon01 box. Note the large voids that maintain porosity.

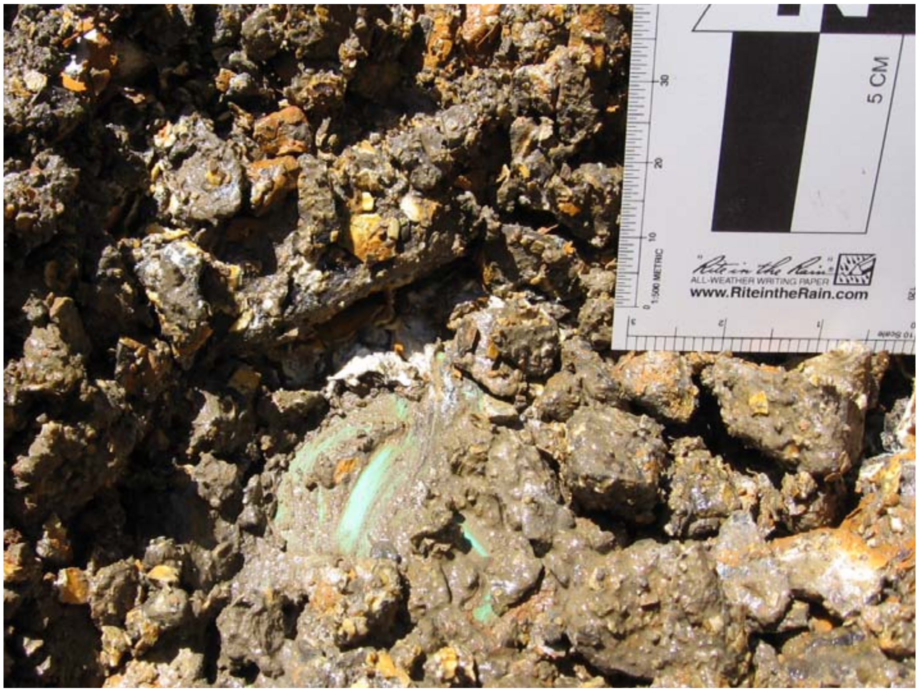


Photo 16. Exposed underdrain pipe in the Jonathan Run Box 1 system. Solids accumulation was evident immediately adjacent to perforations.

Photo 17. Coated stone in the Jon01 box. This scale readily washed off.

Photo 18. Washing Jon01 limestone with pumped fresh water.

Photo 19. Mitchell Tank limestone cleaning. Cleaned limestone is visible in the left side of the tank. The excavator is sitting on top of limestone that has not yet been cleaned.

Photo 20. Mitchell Tank limestone cleaning. Standing water sump used to mechanically wash stone. Black pipe is effluent pipe carrying solids out of the system to the settling pond.

Photo 21. Effluent from Mitchell Tank during limestone cleaning. Solids washed from the system were retained in the settling pond.

Photo 22. Solids washed from limestone in the Mitchell Tank.

Photo 23. Mitchell Tank limestone before cleaning (top) and after cleaning (bottom).

Photo 24. Revised discharge from Mitchell tank.

Photo 25. Flow distribution system installed in West Box.

Photo 26. Cleaning of East Box limestone in a stone box. Raw discharge water was used to wash stone.

Photo 27. Cleaning of East Box limestone in a stone box. Note solids ccumulation inside the stone box.

Photo 28. Comparison of cleaned limestone (left) and uncleaned limestone (right) in the East Box.

Photo 29. Limestone covered with a scale of metals solids in the Mitchell Tank. The dark patches on the surface of the stone mark contact points with adjacent aggregate particles.

Photo 30. Scale flaking off of limestone in the Jonathan Run Box 1 system.

Photo 31. Suspended solids filling aggregate void spaces in the Jonathan Run Box 3 system.

Photo 32. Open void spaces in scale coated limestone of the Mitchell Tank system.