ACIDIC MINE DRAINAGE ABATEMENT IN AN ANAEROBIC SUB-SURFACE FLOW WETLAND ENVIRONMENT - CASE HISTORY OF THE TREATMENT SYSTEM AT CORSICA, PA[1]

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Abstract. Wetland Treatment Systems (WTS) have been constructed over the past decade for the treatment of Acidic Mine Drainage (AMD). Potential benefits of anaerobic sub-surface flow treatment were initially identified from attempts to improve effectiveness of a surface flow wetland at the Jennings Environmental Education Center in western Pennsylvania (Dietz and Stidinger 1993) which, although not completely successful, resulted in acidity removal rates two to four times greater than pre-modification rates. This study was conducted to investigate the potential benefits of sub-surface flow design, which utilizes a sub-surface collection system, in comparison to conventional surface flow design. Two field-scale WTS, each containing anaerobic surface flow and sub-surface flow treatment cells (approximately 100 m^2 each), were constructed along an existing AMD discharge, near Corsica, Pennsylvania, with a 3-4 pH, 250-400 mg/L (as $CaCO_3$) acidity, 20-40 mg/L iron, 15-40 mg/L manganese and 10-30 mg/L aluminum. Sampling of the WTS included two elements: a weekly monitoring program from March 1992 through November 1992 to collect discharge water quality data; and a post-monitoring pore water sampling program conducted on December 8, 1992. Sub-surface flow design was found to provide statistically greater acidity removal with an average rate of 61.8 grams per day per square meter (GDM), in comparison to surface flow which had an average rate of 4.78 GDM, and provided effluent alkalinities greater than 100 mg/L (as $CaCO_3$) and pH greater than 6.5 at the flows and loadings evaluated. Removal rates for iron and aluminum removal of 3.02 and 2.48 GDM in the sub-surface flow design were also significantly greater than surface flow design which had removal rates of 1.89 and 0.20 GDM, respectively. Manganese removal was ineffective in both surface and sub-surface flow designs. Based on pore water results of two sub-surface flow units receiving different AMD flow and loading, an acidity removal rate of 25 GDM is recommended for future wetland treatment systems constructed with the sub-surface flow design evaluated in this study.

Key Words: Acidic mine drainage, passive treatment, wetland treatment, water quality, remediation

Key Phrases: Acidic Mine Drainage remediation utilizing passive (wetland) treatment systems.

Introduction

Wetland Treatment Systems (WTS) have been constructed over the past decade for the treatment of Acidic Mine Drainage (AMD). These WTS have achieved variable and at times inconsistent success at improving and meeting established effluent limits. The variable success of WTS is attributable to differences in design, size and treatment material. Although treatment success is variable, all constructed WTS have, at a minimum, been successful in reducing chemical costs associated with AMD treatment and pollutant loading to receiving streams.

Recent investigations by Hedin *et al.* (1991) have proposed design (sizing) criteria for surface flow compost WTS based on removal rates for iron, manganese and aluminum. In a study by Dietz and Stidinger (1993) on constructed surface flow wetlands, the removal of acidity was correlated with the removal of iron and aluminum, but

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did not find any relationship between acidity removal and manganese removal. Based on these relationships and the consistency of acidity removal in the different wetlands, Dietz and Stidinger (1993) recommended the use of acidity as a design criteria.

Potential benefits of a new WTS design were originally identified at a WTS constructed at the Jennings Environmental Education Center (Dietz and Stidinger 1993). The system was originally constructed as a surface flow system; however, due to poor performance, the WTS was modified by placing limestone and drainline in trenches, to promote greater subsurface flow. The modifications decreased acidity, iron and aluminum and resulted in acidity removal rates 2 to 4 times greater than surface flow WTS.

The following is a summary of several components of the study "Technical Investigation of the Abatement of Acid Mine Drainage in a Sub-surface Wetland Environment" (Dietz et *al.* 1993). This study was to investigate the potential benefits of this WTS design, which utilizes a sub-surface collection system, in comparison to conventional surface flow WTS design and position (i.e., before or after) of surface flow when used in combination with the sub-surface flow systems.

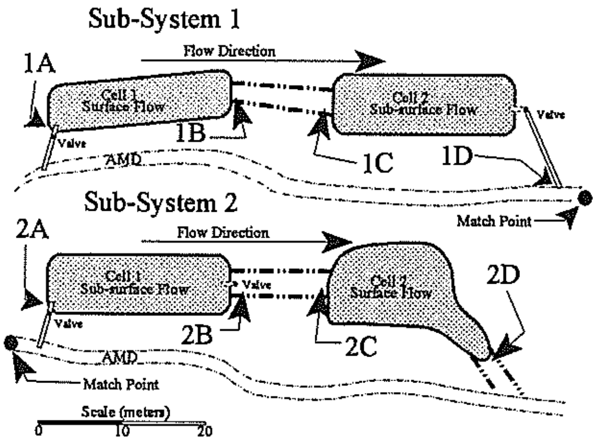

Figure 1. Plan view for the AMD wetland treatment system near Corsica, PA.

Wetland Design

The experimental system, designed to compare surface flow to sub-surface flow design and the two types of designs when used in combination, contained two wetland treatment systems, each containing a sub-surface and surface flow treatment cell. The order in the first treatment system (Sub-system 1) was surface flow followed by sub-surface flow. The order was reversed in the second treatment system (Sub-system 2) to permit evaluation of the two design combinations. Plan view of the two systems and cross-sections of surface flow and sub-surface flow units are contained on Figure 1 and 2.

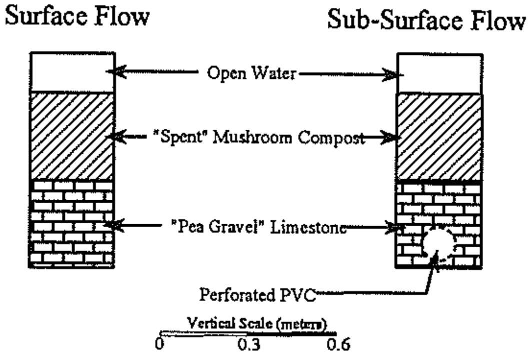

Figure 2. Typical cross-sections of units at the wetland treatment system near Corsica, PA.

The physical parameters of the treatment units consisted of at least 0.5 m of freeboard, a minimum slope of a 1:1 ratio for the inside and outside slopes, and 0.6 m berm width. The cell bottoms and banks of the treatment units were lined with clay found on-site during the excavation process. The surface area of Sub-system 1 totaled 303 m^2 with Cell 1 containing 113^{2}m and Cell 2 containing 130 m^2. The surface area of Sub-system 2 totaled 318 m^2 with Cell 1 containing 116^{2}m and Cell 2 containing 176 m^2.

After installation of the underdrain collection system in the sub-surface flow cells, "pea gravel" limestone purchased from Central Valley Aggregates was placed in each cell to a depth of 30 cm. The stone was covered with "spent" mushroom compost, obtained from Moonlight Mushrooms (Indiana, PA), to a depth of 30 cm. Once the compost was in place, the cells were allowed to fill and all areas disturbed by the construction activities were mulched and seeded with a grass/legume mix. After a two week waiting period the cells were planted by placing dug plant units, consisting of one mature cattail (*Typha latifolia*) and roughly a 30 cm diameter of soil 25 cm thick, on approximately 0.6 m centers. Planting was completed in June of 1991.

Each sub-system received AMD from the same source and at the same flow rate of 11.4 L/min, which were controlled by intake gate valves. In addition to influent flow, gate valves and/or pipe weirs were located between treatment cells and at discharge locations to control and monitor flow through the WTS.

Sampling Program

The sampling program included several elements: a weekly monitoring program to collect discharge water quality data; and a pore water sampling program. The later program was conducted to evaluate wetland processes and functions. The different programs are discussed below.

Weekly Monitoring

For the weekly monitoring program, sampling stations were located in the two sub-systems to collect influent AMD, effluent from each sub-system and intermediate points between individual treatment units. Sampling stations, 1A through 2D on Figure 1, were located to sample influent, discharge, and intermediate locations in each sub-system at weirs and gate valves.

Sampling of the wetland was initiated in May of 1991; however, the severe drought during the early spring and summer of 1991 resulted in a loss of AMD flow in August. Flow did not return until early March of 1992 and normal water levels and sufficient AMD flow did not return until late March 1992. The weekly sampling was re-instated on March 25, 1992, continued through the spring, summer and fall of 1992 and was concluded on November 19, 1992. A total of 35 weekly samples were collected during the second year of the program.

Field measurements for temperature and flow were determined weekly at each sampling station. Temperature was measured with a YSI Model 51B Dissolved Oxygen meter. Estimates of flow were performed using a calibrated bucket (in liters) and a stop watch.

Water samples for laboratory analysis were collected weekly at each station, except influent stations in each sub-system, which were collected on alternating weeks. Samples were collected in 500 mL polyethylene bottles and, due to close proximity of the project (approximately 15 min.), transported to the laboratory in a cooler at the collected temperature. Water samples were analyzed for a number of parameters including: pH by electrometric method using an Orion (Ross) combination electrode; conductivity using a Markeson Model 10 and electrode cell; alkalinity and acidity by the potentiometric titration (H_2O_2) method; sulfate by the turbidimetric method; iron by the phenanthroline method; aluminum by the eriochrome cyanine R method; manganese by the periodate oxidation method; and calcium and magnesium (hardness), directly and indirectly, using the EDTA titrimetric method (APHA 1989 and HACH 1990).

Pore Water Monitoring

Pore water sampling was conducted on December 8, 1992 upon the completion of the weekly monitoring program. Pore water was extracted at the influent and effluent of each treatment pond at various depths from the compost layer; this was dependent on the depth of compost found at each sampling location. In general, pore water was extracted just below the surface, at 15 cm and 30 cm at each location. Cell 2 of Sub-system 2 contained only 15 cm of compost and could only be sampled at the surface and 15 cm depth.

Pore water samples were collected using a negative pressure apparatus that consisted of an 125 mL erlenmeyer flask, a hand held vacuum pump, and a variety of tubing, connectors and rubber stoppers. Collected pore water samples were numbered according to station and stored in air tight containers and transported to the laboratory. The samples were immediately analyzed (within 12 hours of collection) for Eh, pH, ferrous iron and sulfide. Eh was measured with an Orion combination redox electrode in a closed cell. Sulfide was measured on extracted water by the methylene blue method (APHA 1989). The remaining parameters, pH, alkalinity, acidity, total iron, ferrous iron, sulfate and conductivity were analyzed in accordance with procedures previously identified.

Results and Discussion

The results of the research project are summarized below. As reported earlier, a period of no flow

Table 1. Summary of averages and standard errors (in parenthesis) for water quality parameters of special interest monitored at the Corsica, PA wetland treatment system (n=35).

Sample Number	Lab pH	Alkal. mg/L	Acidity mg/L	Total Fe mg/L	Total Mn mg/L	Total Al mg/L	SO_4^{-2} mg/L	Ca mg/L	Mg mg/L
Sub-system 1									
Influent	3.41 (0.0002)	0 (0)	375 (96.8)	34.4 (12.7)	33.6 (6.80)	19.9 (8.55)	1579 (292)	315 (47.)	148 (33.)
Cell 1 Effluent	3.26 (0.0002)	0 (0)	340 (84.7)	20.1 (8.75)	31.8 (6.75)	18.4 (7.81)	1481 (294)	314 (61.)	144 (36.)
Cell 2 Influent	3.27 (0.0002)	0 (0)	232 (60.8)	15.8 (5.61)	32.4 (5.18)	10.8 (4.19)	1458 (285)	320 (47.)	134 (32.)
Cell 2 Effluent	6.76 (1e-7)	112 (21.0)	0 (0)	7.1 (5.44)	33.0 (4.29)	0.06 (0.03)	1351 (260)	377 (61.)	134 (35.)
Sub-system 2									
Influent	3.41 (0.0002)	0 (0)	375 (96.8)	34.4 (12.7)	33.6 (6.80)	19.9 (8.55)	1579 (292)	315 (47.)	148 (33.)
Cell 1 Effluent	6.62 (1.e-7)	112.3 (14.2)	0 (0)	11.13 (7.72)	38.21 (7.76)	0.055 (0.03)	1555 (288)	416 (67.)	160 (37.)
Cell 2 Influent	6.69 (1.e-7)	103.3 (13.7)	0 (0)	6.94 (6.04)	37.37 (7.62)	0.034 (0.02)	1537 (259)	422 (65.)	155 (34.)
Cell 2 Effluent	6.87 (8.e-8)	98.1 (16.5)	0 (0)	0.511 (0.32)	33.72 (5.93)	0.026 (0.02)	1496 (311)	408 (73.)	154 (40.)

occurred during the drought of 1991, which resulted in lowered water levels in several of the treatment units and caused air exposure to the mushroom compost and limestone layers. Therefore, only the data collected in the second year is included.

Effluent Water Quality

Discharge water quality is an important consideration in evaluating WTS performance and the ability of the treatment system to meet required effluent goals and regulatory limits (e.g., pH, iron, aluminum and manganese). The averages of the 35 samples collected for each of the monitoring stations for key parameters included in the sampling program are summarized in Table 1. To evaluate performance, effluent water quality from sub-systems and cells within sub-systems were statistically compared to influent water quality using an ANOVA procedure (Sokal and Rohlf 1981). A probability (p) of 0.05 was selected as the criteria for significant differences.

Temperatures monitored at stations within the sub-system averaged 13°C (55° F) during the monitoring program and varied over the course of the study from 4 to 26°C (40 to 79° F) in the treatment units. No significant effect of temperature was observed on discharge quality of any monitored parameter.

Three parameters that are closely related, pH, acidity and alkalinity, were similarly effected by the sub-systems. The pH in both Sub-systems increased significantly from influent pH of approximately 3 to effluent pH averages greater than 6.5, which is an almost complete removal of hydrogen ions by both sub-systems. The observed pH increases were associated with the sub-surface flow units, Cell 2 in Sub-system 1 and Cell 1 in Sub-system 2. Acidity followed a similar pattern as pH, significantly decreasing from influent concentrations of greater than 350 mg/L (as $CaCO_3$) to effluent aciditities of 0 mg/L in both sub-systems, with the majority of acidity decreases occurring in the sub-surface flow units. The remaining parameter, alkalinity, significantly increased across both sub-systems from 0 mg/L to approximately 100 mg/L (as $CaCO_3$) effluent alkalinity which entirely occurred in the sub-surface flow units of both sub-systems. Slight decreases in alkalinity were observed across Cell 2, the surface flow unit in Sub-system 2, however, the decreases were not significant.

Two of three permit metals, iron and aluminum, decreased significantly across both sub-systems. Manganese, the third metal, did not significantly decrease across either sub-system; although slight increases and decreases of less than 2 mg/L were observed across individual units. Total iron decreased to approximately 7 mg/L in Sub-system 1 and less than 1 mg/L in Sub-system 2. With respect to individual treatment performance, total iron removal was similar across both units in each sub-system, ranging between 20 and 40 percent. A slight increasing trend in total iron was observed in effluent samples from sub-surface flow cells over the 35 weeks of the study, from initial concentrations of less than 5 mg/L to slightly greater than 10 mg/L. Total aluminum levels were found to decrease in both Sub-system 1 and 2 by almost 100 percent to effluent concentrations of less than 0.5 mg/L. Decreases in aluminum occurred in all treatment units, but predominately occurred in the sub-surface flow units and were directly related to the pH increases observed these units which is likely the result of aluminum pH dependent solubility (Stumm and Morgan 1981).

Calcium and magnesium were two metals monitored in the study to evaluate wetland processes. Calcium concentrations significantly increased across both sub-systesms by between 50 and 100 mg/L. The increases in calcium were associated with the sub-surface flow units in both sub-systems; no calcium concentration increases were observed across surface flow units. The observed calcium increases are likely the result of limestone dissolution in the sub-surface flow units, contributing at least 60 percent of the observed alkalinity increases from each sub-system. This alkalinity is important for the neutralization of acidity and hydrolysis and precipitation of metals. Conversely, magnesium concentrations were not significantly affected across either sub-system. Slight decreases of less than 15 mg/L were observed across Sub-system 1 and slight increases of less than 10 mg/L were observed across Sub-system 2, however, neither were significant. The magnesium data provide additional support that the increases in calcium were in fact due to limestone dissolution and not from some other process, such as evaporation.

Sulfate, monitored to evaluate processes within the wetland treatment system, was found to significantly decrease in Sub-system 1 by greater than 200 mg/L. Slight decreases of approximately 80 mg/L in Sub-system 2 were not significant. Sulfate exhibited decreases in both Cell 1 and Cell 2 in Sub-system 1 averaging decreases of approximately 100 mg/L in each cell. Seasonal increases and decreases in effluent sulfate concentrations were apparent in both sub-systems, however, influent sulfate data appeared to follow a similar seasonal change. The sulfate removal observed in the treatment units may reflect acidity removal processes (e.g., biological sulfate reduction) in the treatment systems which can be important for metal sulfide precipitation and alkalinity generation.

The effluent results indicate that the passive treatment systems remediate the majority of pollutants in the AMD. With respect to compliance levels associated with the mining industry, both sub-systems adequately reduced aluminum and raised pH to compliance levels. Only Sub-system 2, the sub-surface flow followed by surface flow configuration, adequately removed iron to levels below permit effluent limits. Neither sub-system lowered manganese which suggests additional treatment for manganese removal would be required to achieve compliance.

Removal Rates

Influent and effluent water quality data from each sub-system were used to determine loadings, removal rates and fluxes for each sub-system and units within each sub-system for iron, aluminum and acidity parameters. These three parameters were of interest since they were all significantly removed by the treatment systems. Loading rates, in grams per day (GPD) were calculated using influent concentration and flow data collected at each cell. Removal rates, also in GPD, were calculated using influent and effluent flow and concentration data. Average removal rates were adjusted to unit area rates or fluxes, in grams per day per square meter (GDM), using the surface areas of each unit.

Loading and removal rates for the sub-systems and individual units are contained in Table 2. The loading rates to the two sub-systems and surface flow unit, Cell 1 in Sub-system 1, and sub-surface flow unit, Cell 1 in Sub-system

2, were similar for all parameters, differing by less than 4 percent. Removal rates for each of the units were much more variable, differing by greater than 100 percent. A summary for each parameter is contained below.

Table 2. Average loading, removal, and flux rates for the Corsica, PA wetland treatment system.

Unit	Factor	Loading GPD	Removal Rate GPD	Flux Rate GDM
Sub-System 1				
Cell 1	Fe	528	214	1.89
	Al	295	22.5	0.20
	Acidity	5740	540	4.78
Cell 2	Fe	148	79.7	0.61
	Al	97.9	97.4	0.75
	Acidity	2170	3210	24.7
Total	Fe	528	338	1.12
	Al	295	187	0.62
	Acidity	5740	4760	15.7
Sub-System 2				
Cell 1	Fe	515	351	3.02
	Al	289	288	2.48
	Acidity	5530	7170	61.8
Cell 2	Fe	75.4	70.7	0.4
	Al	0.32	0.093	0.01
	Acidity	-1000	-42.7	-0.2
Total	Fe	515	465	1.46
	Al	289	288	0.91
	Acidity	5530	7030	22.1

Removal rates for acidity which reflect the addition of alkalinity to the effluent for Sub-system 2 were greater than Sub-system 1. The differences between sub-systems were not the result of differences in sub-system performance, but due to an uncontrollale loss of flow between Cell 1 and 2 of Sub-system 1, resulting in lower acidity loading and removal potential in the sub-surface flow unit (Cell 2). Removal rates adjusted for treatment area or fluxes for the sub-systems were similar, approximately 20 GDM, however, individual treatment unit fluxes were much more variable ranging from 0 to 60 GDM. As was indicated by the concentration results, acidity removal was predominately associated with the two sub-surface units. Fluxes for Cell 1 in Sub-system 2 (sub-surface flow) was 61 GDM, which was almost three times greater than the flux of 25 GDM for Cell 2 in Sub-system 1; however, the later unit received less than half the loading (2170 GPD vs. 6630 GPD). The surface flow unit from Sub-system 1 had a flux of 4.8 GDM which is similar to values obtained by other investigators (Dietz and Stidinger 1993 and Hedin *et al.* 1994) for anaerobic surface flow design. The removal rate for Cell 2 in Sub-system 2 is of limited value due to the absence of influent acidity.

Total iron removal rates were slightly greater in Sub-system 2, by slightly more than 100 GPD, than removed in Sub-system 1 which corresponds to slightly greater effluent iron measured from this sub-system (see Table 1). Total iron fluxes for Sub-system 2 were also slightly greater than Sub-system 1, 1.12 GDM versus 1.46 GDM, respectively. Fluxes were greatest in the first treatment units of both sub-systems and were coupled with the highest iron loadings. This relationship between iron removal and iron loading was also observed by Dietz and Stidinger (1993) in surface flow wetlands receiving various iron loadings.

Effluent total aluminum was essentially zero from both sub-systems, and differences in removal of aluminum, removal rates of 187 GPD for Sub-system 1 and 288 GPD for Sub-system 2, were due to previously discussed flow loss in Sub-system 1. Aluminum decreases across each sub-system were primarily associated with the sub-surface flow units, which had fluxes at least three times greater than the highest flux observed in the surface flow units, Cell 1 of Sub-system 1.

Pore Water Results

Pore water results from each treatment unit, average of influent and effluent samples, are summarized in Table 3. The pore water pH found in the compost of Cell 1, the surface flow unit in Sub-system 1, increased within the first several centimeters of compost depth from less than 4 to near 7. Cell 2, the sub-surface flow unit of Sub-system 1, did not have observable pore water pH increases until near the bottom of the compost layer which had

Table 3. Average of influent and effluent pore water results from the treatment units at the Corsica, PA wetland treatment system (n=2).

Cell	Depth cm	Eh mV	LAB pH	Alkal. mg/L	Acidity mg/L	Fe^{+2} mg/L	SO_4^{-2} mg/L	H_2S mg/L
Sub-System 1								
1	300	220	3.55	0	230	40.3	1000	0.84
	15	-275	6.45	460	0	16.7	1060	6.0
	30	-205	6.75	900	0	38.0	800	1.32
2	0	66.	4.41	2	244	7.7	785	0.84
	15	-168	4.49	2	236	10.5	1130	3.59
	30	-208	6.28	50	0	21.6	1250	0.78
Sub-System 2								
1	0	470	3.37	0	374	3.78	1350	0
	15	173	3.62	0	248	9.66	1300	0.55
	30	-55	4.20	0	332	15.0	1200	1.46
2	0	-67	6.53	159	0	25.5	1090	0.03
	15	-204	6.95	356	0	4.94	1190	3.21
	30	-197	7.11	826	0	5.46	955	0.67

pH levels near 6. Cell 1, the sub-surface flow unit of Sub-system 2, only had increases in pore water pH from slightly above 3 to approximately 4, less than a 1 unit pH increase. Similarly the increases in pore water pH in Cell 2 of Sub-system 1 were less than 1, however, surface water pH was well above 6 which did not allow for more substantial increases.

Pore water Eh, a measure of redox potential, decreased with depth in the compost in all units from values greater than 0 mV to less than -200 mV, except Cell 1 of Sub-system 2 which had decreases only to approximately -100 mV. The Eh decreases were fairly rapid occurring in the upper 15 cm of compost.

Acidity in pore waters tended to decrease with depth in the treatment units while alkalinity tended to increase with depth. Only pore waters from Cell 1 of Sub-system 2 contained acidity concentrations and no alkalinity at all depths. Surface flow units contained highest alkalinities in pore waters with maximum concentrations exceeding 800 mg/L. This is of particular interest for Cell 1 of Sub-system 1 since alkalinity was not measured in the effluent during the weekly monitoring program. Sub-surface flow units contained higher acidity concentrations and the lower alkalinity concentrations than surface flow units. This observed effect is likely the result of increased penetration of the AMD into the substrate, as a result of the underdrain systems, than would occur in surface flow design where diffusion across the water/compost barrier is relied upon.

Sulfate concentrations in the pore water of the two surface flow units were similar. Concentrations increased by less than 100 mg/L from surface concentrations to the 15 cm depth before decreasing to well below surface water concentrations at the 30 cm depth. Sulfate concentrations in the sub-surface flow units differed from each other and the surface flow units. Cell 2 of Sub-system 1 contained increasing concentrations of sulfate with depth, whereas pore water sulfate in Cell 1 of Sub-system 2 decreased by approximately 150 mg/L throughout the 30 cm compost depth. Sulfide concentrations, the other sulfur form monitored, were detected at depths in the compost in all treatment units with maximum concentrations ranging between 2 and 8 mg/L. Maximum sulfide concentrations tended to occur at the middle depth of 15 cm.

The low Eh (less than -100 mV) and elevated pH (greater than 4) in pore waters collected from the treatment units indicate that conditions are conducive for biological sulfate reduction (Dietz 1989). Sulfate was found to decrease with respect to depth in several units which, in combination with the elevated sulfide concentrations, clearly indicates this process occurs in the units. The processes benefits in improving AMD quality are reflected in the higher pH and alkalinity observed in pore waters.

The differences in pore water data between surface flow and sub-surface flow design are apparent for all the parameters evaluated. Surface flow units contained higher pH, lower Eh, higher alkalinity and higher sulfide in pore waters than sub-surface flow units. The differences are likely the result of increased interaction of AMD with the compost layer in sub-surface flow units from directing the AMD through the compost with the underdrain system. The importance of this greater interaction is apparent in effluent results from the sub-surface flow units which had effluent higher in pH, lower in acidity, and higher in alkalinity than the surface flow unit.

Differences in sub-surface flow unit pore water Eh, pH and acidity were also observed. These differences are likely the result of differences in AMD loading to the two units, as identified in the previous section (see Table 2), where Cell 1 in Sub-system 2 received higher AMD loading than Cell 2 in Sub-system 1.

Sub-surface Flow vs. Surface Flow Comparison

A statistical analysis was conducted to compare water quality monitoring data from surface flow design (Sub-system 1 - Cell 1) and sub-surface flow design (Sub-system 2 - Cell 1) in order to evaluate the beneficial effects of the sub-surface flow treatment design over conventional surface flow design. The analysis consisted of comparing water quality monitoring data for individual parameters using an ANOVA procedure (Sokal and Rohlf 1981). Parameters included in this analysis were selected based on effluent requirements of wetland systems (i.e., pH, acidity, alkalinity, total iron, total manganese, and aluminum) and wetland processes (i.e., sulfate, calcium and magnesium).

The average pH discharged from the sub-surface flow design was significantly ($p<0.001$) higher, greater than 3 units, than the average pH discharged from the surface flow design. In comparison to surface flow, which discharged significantly ($p<0.001$) higher concentrations of acidity and no alkalinity, sub-surface flow discharged significantly ($p<0.001$) greater concentrations of alkalinity and no acidity. Iron and aluminum concentrations discharged by sub-surface flow were also significantly ($p<0.001$) lower than the surface flow units; iron and aluminum concentrations were approximately 10 mg/L and 20 mg/L lower, respectively. Conversely, manganese concentrations were significantly higher, approximately 6 mg/L, from sub-surface flow than surface flow. Calcium, analyzed to evaluate processes, was significantly different between the two designs. Calcium measured significantly ($p<0.001$) greater, approximately 100 mg/L, in the discharge from sub-surface flow than surface flow. The remaining two parameters, sulfate and magnesium, had averages that were slightly different between flow designs; however, the differences were not significant.

This comparison clearly indicates the anaerobic sub-surface flow design has superior AMD remediation capabilities than surface flow design for this type of AMD discharge. Water quality improvements were significantly better for all parameters evaluated except manganese, however, neither design afforded any measurable decreases in manganese concentrations. In addition, the superior effluent water quality results in higher removal rates for most of the parameters, except manganese, in sub-surface flow which would be reflected in reduced treatment area for sub-surface flow design. The improved effluent water quality from sub-surface flow may be, in part, the result of improved interaction of the AMD with the compost. In addition, the importance of higher calcium concentrations from sub-surface flow, which are the result of limestone solubilization, may be the result of improved contact of the AMD with the limestone layer.

Sub-System Comparison

A statistical analysis was also conducted, similar to the sub-surface flow and surface flow comparison, to compare water quality monitoring data from Sub-system 1 to Sub-system 2 to determine which configuration afforded better effluent water quality; see Table 1 for comparison of effluent means.

The average pH values discharged from the sub-systems were not significantly different. Both systems provided complete removal of acidity throughout the monitoring program. A slightly higher (approximately 14 mg/L) average alkalinity was discharged by Sub-system 1 in comparison to Sub-system 2; this was found to be significant ($p<0.005$). Sub-system 2 exhibited an average total iron of less than 1 mg/L, which was significantly ($p<0.001$) lower than the 7.1 mg/L average total iron exhibited by Sub-system 1. In addition, the average aluminum concentration from Sub-system 2 was significantly ($p<0.001$) lower than the level from Sub-system 1; however, in both sub-systems the average aluminum levels were well below 1 mg/L. The remaining metal analyzed, manganese, was not significantly different between the two sub-systems.

Sulfate, a process parameter, was significantly ($p<0.025$) different between the two sub-systems. On average, sulfate concentrations were approximately 150 mg/L lower in Sub-system 1 than in Sub-system 2. The remaining two parameters, calcium and magnesium, had averages that were slightly higher for Sub-system 2 than Sub-system 1; however, the differences were not significant.

The only effluent water quality parameter effected by placement of the sub-surface and surface flow units was iron. The Sub-system 2 configuration, sub-surface flow followed by surface flow, yielded iron concentrations significantly lower than Sub-sytem 1 and to levels necessary to meet compliance concentrations. This suggests sub-surface flow followed by surface flow will be the preferred configuration in a two cell treatment design.

Summary

Wetland design has been evolving over the past decade. Recent studies have begun to recommend sizing criteria that are intended to provide guidance in designing wetland systems (e.g., Hedin *et al.* 1994 and Dietz and Stidinger 1993), however, this design information has been limited to surface flow designs. The results from this research treatment project provided water quality and design information regarding sub-surface flow design. In addition, the study provided guidance with respect to placement of sub-surface flow and surface low treatment units when used in combination.

The water quality monitoring data clearly indicated that sub-surface flow design produces water quality that is superior to surface flow design for a number of parameters that include pH, iron, aluminum, acidity and alkalinity. Neither wetland design significantly removed manganese; however, manganese removal would not be expected in strongly reducing environments, as is found in compost wetland treatment systems, where solubility of manganese tends to increase (Stumm and Morgan 1981).

The water quality monitoring data also identified the appropriate alignment of a two cell system utilizing sub-surface and surface flow units. Water quality was similar between the two sub-systems for pH, aluminum, acidity and alkalinity. Effluent iron levels (approximately 0.5 mg/L) in Sub-system 2 were significantly lower than effluent iron levels (approximately 7 mg/L) in Sub-system 1 which indicates sub-surface flow followed by surface flow is the better alignment.

Processes in the wetlands important for remediating the high acidity in AMD were qualitatively evaluated. Alkalinity generating processes identified in the wetlands were sulfate reduction and limestone dissolution. Based on calcium increases in sub-surface flow units limestone dissolution accounted for greater than 60 percent of the alkalinity generated.

Acidity removal rates, identified by Dietz and Stidinger 1993 as the most reliable design parameter for determining size of wetland systems constructed for AMD treatment, were 24.7 GDM and 61.8 GDM in the two sub-surface flow cells. Lower pH, higher Eh, and higher acidities observed in pore water collected in the compost of the sub-surface flow cell in sub-system 2, which had a flux rate of 61.8 GDM, suggest the cell may have been overloaded. Therefore, a design criteria of 25 GDM for acidity removal, based on acidity flux measured in Cell

2 of Sub-system 1, is recommended for predicting size of future sub-surface flow wetland treatment systems.

The intent of the study was not to evaluate life expetancy of the sub-surface flow design. Life expetancy of sub-surface flow systems will likely be affected by a number of factors associated with the chemistry of the AMD, materials placed in the sub-surface flow system and design features (e.g., aerobic pre-treatment) intended to reduce excessive precipitation of metals in sub-surface flow systems. Long-term operational data from systems based on the above design guidance will be required to assess long-term effectiveness of the sub-surface flow design.

Literature Cited

American Public Health Assoc. (APHA). 1989. Standard methods for the examination of water and wastewater, 17th edition. APHA. New York.

Dietz, J.M. 1989. Biogeochemistry of iron and sulfur in laboratory sphagnum microcosms treated with a synthetic acidic mine water. M.S. Thesis. PA State Univ. University Park, PA.

Dietz, J.M. and D.M. Stidinger. 1993. Evaluation of wetlands constructed for the treatment of acidic mine drainage. Prepared by The EADS Group, General Engineering Division, for the PA Dept. of Environmental Resources, Division of Mine Hazards, Harrisburg, PA. SL 1015-101.2

Dietz, J.M., J. Gruver, and D.M. Stidinger. 1993. Technical investigation of the abatement of acid mine drainage in a sub-surface wetland environment. Prepared by The EADS Group, General Engineering Division, for the U.S. Bureau of Mines. Contract J0209007

HACH Company (HACH). 1990. Water Analysis Handbook, 2nd edition. Printed by the HACH Company, Loveland, CO. 800p.

Hedin, R.S., D.H. Dvorak, S.L. Gustafson, D.M. Hyman, P.E. McIntire, R.W. Nairn, R.C. Neupert, A.C. Woods and H.M. Edenborn. 1991. Use of constructed wetlands for the treatment of acid mine drainage at the Friendship Hill National Historic Site, Fayette County, PA, Final Report. Environmental Technology Group, U.S. Dept. of the Interior, Bureau of Mines, Pittsburgh Research Center, Pittsburgh, PA.

Hedin, R.S., R.W. Nairn, and R.L.P. Kleinmann. 1994. Passive Treatment of Coal Mine Drainage. U.S. Dept. of the Interior, Bureau of Mines. Information Circular 9389. 35p.

Sokal, R.R. and F.J. Rohlf. 1981. Biometry: The Principles and Practice of Statistics in Biological Research, 2nd edition. W.H. Freeman and Company, San Francisco. 859p.

Stumm, W. and J.J. Morgan. 1981. Aquatic Chemistry: An introduction emphasizing chemical equilibria in natural waters, 2nd edition. John Wiley & Sons, New York. 766p.