EVALUATION OF ACIDIC MINE DRAINAGE TREATMENT IN CONSTRUCTED WETLAND SYSTEMS[1]

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Abstract: The Pennsylvania Department of Environmental Resources, Bureau of Abandoned Mine Reclamation, Division of Mine Hazards (DER) has identified wetland treatment as an appropriate technology to reduce impacts of AMD on surface waters. DER constructed six surface flow wetland treatment systems (WTSs) with a variety of designs at three sites; Canoe Creek, Jennings Environmental Education Center, and Cucumber Run. The WTSs were constructed to reduce AMD impacts on receiving streams, to evaluate treatment effectiveness, to evaluate biological and chemical processes, and to develop design criteria for future WTS construction. The majority of constructed WTSs did not achieve the treatment goals for iron (3.0 mg/L), aluminum (5.0 mg/L), and manganese (7.0 mg/L) established by DER. The WTSs did significantly lower metal concentrations (on average) in the AMD for iron by 35% to 95%, aluminum by 0% to 50%, and manganese by 0% to 30%. In addition to metals, the wetland treatment systems also decreased acidity concentrations by 40% to 90%, which should reduce the pH and metal impacts of the AMD on the receiving stream. This project also provided data indicating WTS performance did not substantially diminish for the duration (2 yr) of this study, and observed fluctuations in effluent quality were due to variable influent quality. The results from the WTSs suggest that a number of physical (e.g., settling and absorption), chemical (e.g., hydrolysis), and biological processes (e.g., dissimilatory sulfate reduction) are important for improving water quality. Finally, the project provided invaluable data that indicate acidity removal is the most appropriate parameter for future surface flow WTS design. The study found acidity removal (in grams per day), unlike iron, aluminum and manganese, to correlate with WTS size. In addition, acidity removal was not affected by changes in influent AMD chemistry. Based on the data from this study, a surface flow WTS design criteria of 6 $g/d/m^2$ (1.25×10^{-3} $lb/d/ft^2$) for acidity removal is recommended to predict sizing requirements for future WTS construction.

Introduction

In Pennsylvania, thousands of miles of streams are impacted by acidic mine drainage (AMD), causing degradation of surface water quality and impacts on receiving stream aquatic biota. In many areas of Pennsylvania, AMD originates from the continued oxidation of pyritic minerals primarily associated with abandoned and unreclaimed coal mine (surface and deep) sites. Typically, this AMD is extremely acidic and contains high concentrations of metals (e.g., iron, aluminum, and manganese).

The Department of Environmental Resources, Bureau of Abandoned Mine Reclamation, Division of Mine Hazards (DER) has undertaken reclamation of abandoned mine sites across Pennsylvania to reduce and/or eliminate safety hazards and impacts of abandoned sites on the environment. Owing to long term treatment, low cost, and low maintenance, DER has identified

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wetland treatment as an appropriate technology to reduce the impacts of AMD on surface waters. At the time of this project, information on wetland systems constructed for treatment of AMD was limited. The majority of studies focused on biological and chemical treatment processes (e.g., iron oxidation). Little or no information was available on wetland design and sizing criteria.

This study was a multipurpose project initiated by DER to achieve a number of goals. For the purpose of this project the goals, as defined by DER, include: to evaluate the reduction of iron, aluminum, and manganese concentrations as well as improvements to other AMD pollutants by the constructed WTSs; to evaluate long term operation and maintenance of constructed wetlands; to evaluate chemical and biological processes in wetland systems that may have beneficial impacts on water quality; to establish design criteria from constructed wetlands for use in designing wetlands at future abatement locations.

Three sites, Canoe Creek, Jennings Environmental Education Center, and Cucumber Run, were selected by DER to construct experimental wetland treatment systems (WTS). The results from each site are discussed below.

Site Selection

The Canoe Creek, Jennings Environmental Education Center, and Cucumber Run sites were selected based upon the protection of surface waters and recreational waters, public awareness, and proximity to important recreational resources. Descriptions of each location follow.

Canoe Creek is located in Clarion County and is a tributary to the Clarion River. This stream has been classified by DER as a high quality cold water fishery. A number of AMD discharges from historical surface mining in the upper watershed of Canoe Creek degraded water quality in a first order tributary to Canoe Creek and also threatened water quality in the mainstem. WTSs were constructed on two of the larger discharges (K2 and K3) to reduce pollutant loading to the receiving stream.

Jennings Environmental Education Center (JEEC) in Moraine State Park is located in Butler County along Big Run, which is a tributary to Slippery Rock Creek. Moraine State Park is an important recreational resource to the area, and the JEEC is a public environmental information center. AMD from an abandoned deep coal mine, located on the hillside east of JEEC and Route 8, had discharged across Route 8 and onto an area adjacent to JEEC for a number of years. The AMD had degraded the aesthetic quality of the area adjacent to JEEC and water quality in Big Run (pH depression and increased metals). An attempt was made in the 1970's by the DER to seal the mine; however, the efforts were unsuccessful, and AMD continued to discharge near the JEEC. A WTS was constructed at JEEC to reduce visual impacts of the AMD at the JEEC and improve water quality in Big Run. In addition, DER felt the project could be used as an instructional tool at JEEC for AMD, wetland treatment, and wetland function and values.

Cucumber Run, located in Ohiopyle State Park, is a small cold water fishery that flows over Cucumber Falls, a point of interest in the park, before entering the Youghiogheny River. Historical mining in the Cucumber Run watershed has resulted in the input of AMD to Cucumber Run. The AMD has impacted the cold water fishery and the appearance of Cucumber Falls, and the Youghiogheny River. WTSs were constructed on three discharges (CUC1, CUC2, CUC3) emanating from collapsed deep mine on the North Branch of Cucumber Run. The WTSs were intended to reduce water quality impacts of AMD on Cucumber Run and decrease the aesthetic impacts on the Cucumber Falls and Youghiogheny River.

WTS Design

WTS design involves the integration of biological (e.g., wlfate reduction), physical (e.g., available space), and chemical (e.g., iron concentration) factors. At the time this project was conceived, little was known about design or biological processes involved in the remediation of AMD. As a result, the majority of wetlands were designed with similar features. The basic design utilized in this project was a multicell design with each unit comprised of 1 to 1½ ft (0.3 to 0.5 m) deep of "spent" mushroom compost, a water depth of 0 to ½ ft (0 to 0.1 m) over the compost, and locally transplanted cattails (*Typha lattifolia*) and other plant species. "Spent" mushroom compost was chosen as the substrate material because of local availability and potential advantages as a planting and treatment medium. Cattails were selected because of the specie's colonizing ability in AMD sites. Several WTS designs incorporated slightly different features. Two of the WTSs (K2 and CUC1) included an initial open water basin, because high influent ferrous iron or suspended solids were present. In addition, the K2 WTS incorporated limestone below the compost substrate (fifth pond), which was added to evaluate the effects of this substrate material on WTS effectiveness. Finally, the first and fourth units of the JEEC WTS were modified after construction utilizing a drain line surrounded by limestone in an attempt to direct flow through the compost.

The size of each WTS was based primarily on available area for construction, and multicell designs were incorporated to reduce possible short circuiting. The K2 WTS contained a pretreatment unit and four compost units (approximately 190 m^2 each) for a total treatment area of 952 m^2. The K3 WTS contained three compost units with sizes of approximately 115 m^2 (Cell1), 72 m^2 (Cell 2), and 37 m^2 (Cell 3) for a total treatment area of 224 m^2. The JEEC WTS contained four treatment units with sizes of approximately 224 m^2 (Cell 1), 259 m^2 (Cell 2), 344 m^2 (Cell 3), and 334 m^2 (Cell 4) for a total treatment area of 1,161 m^2. The CUC1 WTS contained one treatment unit with a total area of 1,340 m^2, but contained an open water area that reduced the compost area to 1,140 m^2. The CUC2 WTS was the smallest WTS and contained only two compost units with sizes of 44 m^2 (Cell 1) and 48 m^2 (Cell 2). The CUC3 WTS contained four compost units with sizes of 155 m^2 (Cell 1), 96 m^2 (Cell 2), 86 m^2 (Cell 3), and 123 m^2 (Cell 4) each) for a total treatment area of 460 m^2.

WTS Monitoring Program

Sampling was initiated on the wetlands shortly after construction was completed. Sampling stations were located in WTSs to collect influent, effluent from the WTSs, and intermediate points between individual treatment units. Biweekly and monthly sampling at each WTS was conducted by DER personnel. The duration of sampling at WTSs follows: August 1988 to May 1991 at the K2 WTS; August 1988 to May 1991 at the K2 WTS; August 1988 to May 1991 at the K2 WTS; July 1988 to May 1991 at the K3 WTS; April 1989 to February 1991 at the JEEC WTS; and June 1990 to December 1991 at the CUC1, CUC2, and CUC3 WTS.

The sampling program monitored parameters to provide data regarding WTS treatment effectiveness and treatment processes within the wetlands. Collected water samples were analyzed for pH, alkalinity, acidity, sulfate, total iron, ferrous iron, total manganese, total aluminum, and hardness. In addition, water flow was measured at several sampling locations within each WTS to evaluate loadings and removal rates.

Results and Discussion

The following sections discuss the results of the six WTSs with respect to the goals described in the introduction. For a complete evaluation of results, the document "Evaluation of Wetlands Constructed For The Treatment of Acidic Mine Drainage" (Dietz and Stidinger 1993) is available upon request from DER, Bureau of Abandoned Mined Land Reclamation (Robert G. Watts).

Treatment Effectiveness

WTSs were evaluated with respect to treatment effectiveness for a number of different parameters (i.e., pH, iron, aluminum, manganese, and acidity). The average influent and effluent concentrations from the systems are summarized in table 1. Reduction in iron concentration varied considerably in the WTSs, ranging from greater than 90% (K2) to less than 30% (CUC1) of influent concentrations. The K2 and K3 WTSs decreased iron concentrations on average by more than 90%, the majority of the decreases occurred in the first units and appeared to be the result of ferrous iron oxidation, which accounted for 85% of the decreases in total iron. Similar to the Canoe Creek WTSs, total iron decreases across the CUC2 WTS were related to ferrous iron decreases. The CUC1 WTS received influent iron similar to the K2 WTS (85.6 mg/L), but this WTS only decreased the iron by approximately 28%. Similar to the Canoe Creek

Table 1. Influent and Effluent Averages For Monitored Parameters at WTSs.

WTS	Station	Total Fe (mg/L)	Total Al (mg/L)	Total Mn (mg/L)	Lab[1] pH	Acidity (mg/L as $CaCO_3$)	Sulfate (mg/L)
K2	Influent[2]	98.3	0.80	12.2	4.64	126.5	594
	Effluent	6.7	0.42	8.5	4.90	6.0	462
K3	Influent	41.0	2.4	30.7	5.20	114.3	1,388
	Effluent	2.7	3.4	28.0	4.41	40.6	1,202
JEEC	Influent	22.4	18.5	6.2	2.90	258.4	516
	Effluent	14.5	14.3	6.0	3.33	153.6	519
CUC1	Influent	85.6	15.0	3.9	2.60	392.0	303
	Effluent	61.9	12.0	4.1	2.70	272.0	312
CUC2	Influent[2]	36.3	1.2	4.2	3.27	108.3	718
	Effluent	12.9	1.0	4.8	3.51	56.2	754
CUC3	Influent	10.6	4.2	4.8	3.12	106.5	332
	Effluent	5.5	3.0	4.3	4.01	26.8	313

[1] pH values in table are -LOG transformation of hydrogen ion statistical results.
[2] Influent values are based on flow adjusted averages of multiple influent data.

WTSs, a large fraction of the influent total iron in the CUC1 was comprised of ferrous iron, which decreased from an influent average of 50 mg/L to an effluent average of 14 mg/L; however, unlike the Canoe Creek WTSs, the total iron concentration did not decrease in proportion to the decrease in ferrous iron. The CUC3 and JEEC WTSs received influent iron concentrations lower than the amounts received by all the other WTSs, and decreased total iron concentrations by approximately 50% and 35%, respectively; however, different from the other WTSs, ferrous iron increased from less than 1 mg/L to above 3 mg/L in both WTSs.

Average influent aluminum concentrations ranged from less than 1 mg/L (K2) to a high of 18.5 mg/L (JEEC). Aluminum concentrations decreased slightly across all the WTSs except the K3 WTS, which increased aluminum by 1 mg/L. The maximum decrease in aluminum occurred across the JEEC, which decreased on average by 4.2 mg/L; however, this was only about a 23% decrease. Average manganese received by the WTSs ranged from a low of 3.9 mg/L (CUC1) to a high of 30.7 mg/L. As was observed with aluminum, manganese was slightly lowered across most WTSs except CUC1 and CUC2, which increased manganese on average by 0.2 mg/L and 0.6 mg/L, respectively. The effect that the WTSs had on pH was minimal, ranging from -0.6 in the K3 WTS to 0.9 in the CUC3 WTS. The pH decrease across the K3 WTS may have been related to ferrous iron oxidation and precipitation and may have caused of the aluminum increase, which has a pH dependent sowbility.

The WTSs had a much greater effect on acidity; average acidity decreased across all the systems. The K2 WTS decreased average acidity by more than 120 mg/L (as $CaCO_3$), an almost complete removal of acidity. Acidity would have been removed completely except for a known AMD seep that entered the third compost unit. Three other WTSs (JEEC, CUC1, CUC2) decreased average acidity by more than 100 mg/L with percent decreases ranging from 30% to 65%. The remaining WTSs, K3 and CUC3, decreased average acidity by slightly more than 70 mg/L, which were decreases of 65% and 75%, respectively.

DER established average discharge criteria for iron (3 mg/L), aluminum (5.0 mg/L), and manganese (7.0 mg/L) for the WTSs. Only the K3 WTS achieved iron concentrations below the 3.0 mg/L criteria. Two other WTSs, CUC3 and K2, discharged average iron levels that were reasonably close (a factor of 2) to the effluent criteria. Effluent aluminum concentrations were, for the majority of WTSs, less than the established level of 5.0; however, average influent concentrations at the same systems were also below the established treatment goals. The only WTS that had influent concentrations well above the aluminum treatment goal was the JEEC system with an average influent of 18.5 mg/L, and this system did not lower aluminum concentrations below the effluent goal of 5.0 mg/L. Similar to aluminum, only one WTS (K3) received manganese well above the criteria and the K3 WTS did not substantially reduce manganese.

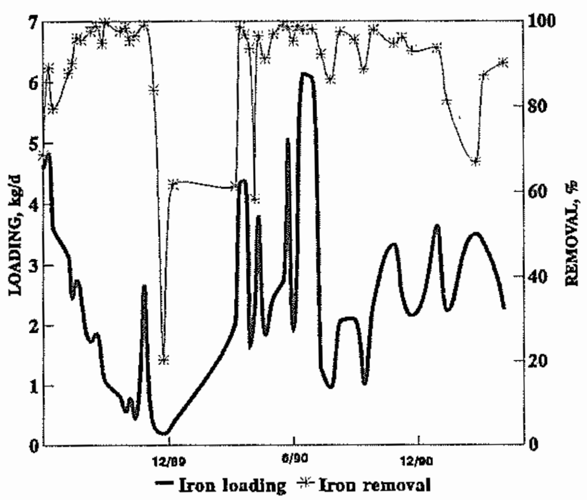

Figure 1. Iron loading and percent iron removal in the K2 wetland treatment system.

Although the treatment goals, in many cases, were not met by the wetland systems, the monitoring data indicate that the WTSs vastly improved AMD water quality. Iron levels were significantly reduced by all WTSs, with removal ranging between 50% and 90% of influent concentrations, and the wetland systems reduced average acidity of the AMD by greater than 40%. The inability of the WTS to achieve the treatment goals is not likely a result of inadequacy of wetland treatment, but due to the general lack of specific knowledge regarding sizing design criteria at the time of this project.

<u>Long-term Operation</u>

Owing to the variability of influent concentrations and flows, effluent concentration data could not be used for evaluation of seasonal and long-term treatment effectiveness. To address seasonal and long-term effluent water quality from the WTSs, influent loading and percent removal for two selected parameters (iron and acidity) were examined for the K2 and K3 WTSs, which were sampled for the longest period of time (over 2½ yr).

Iron loading and removal for the K2 and K3 WTSs are presented in figures 1 and 2. Iron removal remained above 80% in both WTSs throughout much of the monitoring, except for

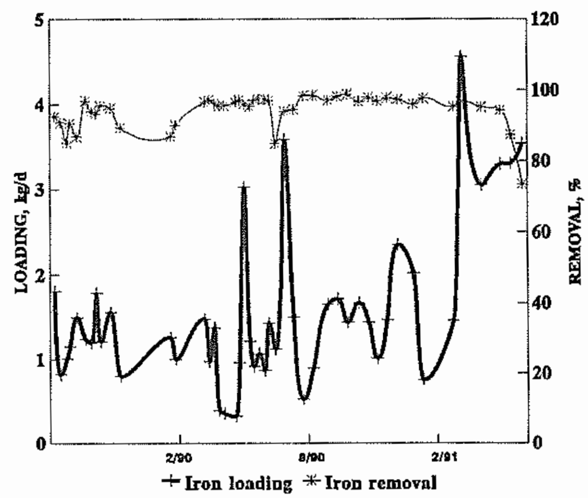

Figure 2. Iron loading and percent iron removal in the K3 wetland treatment system.

several short periods. One period of reduced removal in the K2 WTS corresponded with low iron loading at the end of 1989, which suggests removal may be dependent on loading. A slight decrease in removal at the end of monitoring occurred in both WTSs. The decline in removal in the K3 WTS corresponded with elevated iron loadings well above iron loadings during the previous 2 yr. It is difficult to determine if this is a result of lowered treatment effectiveness of the system or a result of loading.

Acidity loading and removal for the K2 and K3 WTSs, presented in figures 3 and 4, varied considerably over the monitoring period. A period of high removal, greater than 100% (greater than 100% removals are the result of including alkalinity

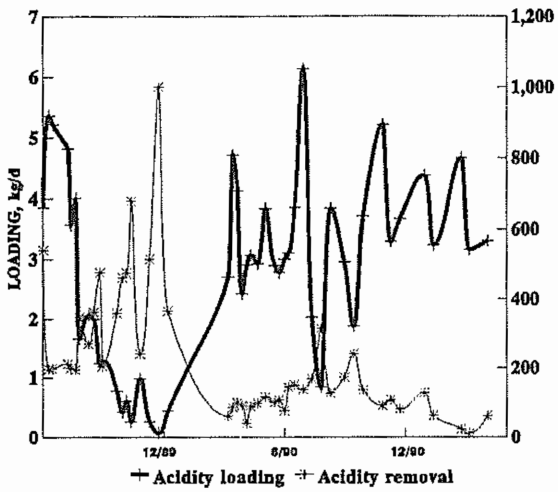

Figure 3. Acidity loading and percent acidity removal in the K2 wetland treatment system.

production), occurred in the K2 WTS around the end of the 1989 monitoring year and was associated with a period of low acidity loading (similar to iron loading in figure 1). Possible seasonal effects on removal may have occurred in both WTSs during the 1990 monitoring year, with higher removal occurring during the warmer growing seasons; however, the variability of loading on the systems, as occurred during 1989 in the K2 WTS, may mask or have caused this observable effect.

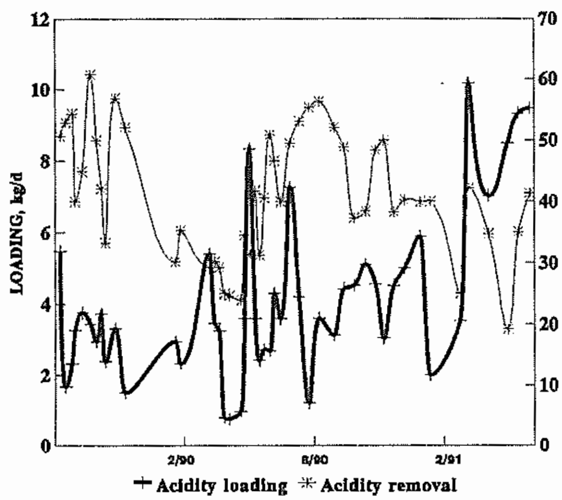

Figure 4. Acidity loading and percent acidity removal in the K3 wetland treatment system.

This long term evaluation of the WTSs is qualitative and somewhat inconclusive. The acidity and iron loading variability received by the WTSs tends to mask or contribute to observed removal trends. Greater controls on flow and concentration of AMD received by the WTSs would be required, which may not be practical or feasible under field conditions. In addition, WTS monitoring for periods longer than 2½ yr may provide a better evaluation of long-term effectiveness.

Wetland Processes

Research has identified a number of biological, chemical, and physical processes (e.g., sulfate reduction and cation exchange) that may be involved in the remediation of AMD in wetland treatment systems. WTS receiving high ferrous iron (i.e., K2, K3, CUC1, and CUC2), a highly soluble form, decreased across the wetland systems (based on monitoring data), suggesting that oxidation processes are involved in lowering ferrous iron and total iron in these wetlands. The low pH conditions (3 to 4) in the Cucumber Run wetlands indicate that chemical oxidation of ferrous iron would have been slow and that oxidation was most likely due to biological oxidation, which has been found to occur in wetland type environments (Gerber et al. 1985, Dietz 1989). The Canoe Creek wetlands had higher influent pH (5 to 6), which suggests, at least in the first units, that chemical oxidation occurred.

Sulfate reduction, an anaerobic process that produces alkalinity, has been found to occur, even at low pH (< 4), in wetland environments affected with AMD (Dietz 1989). Monitoring data from several WTSs (i.e., K2, K3, CUC3) indicate that sulfate concentrations significantly decreased by between 20 and 180 mg/L. Sulfate increased slightly in the other WTSs, which may have been the result of high influent sulfate variability or AMD inflows at intermediate locations in the WTSs. An additional source of acidity removal and alkalinity production may have occurred from carbonate mineral (limestone) solubilization, either from material placed in the wetland (Canoe Creek K2 WTS and JEEC WTS) or from crushed limestone, which is a common additive to mushroom compost. Although no dissolution measurements were made, dissolution of $CaCO_3$ should increase hardness, from the release of calcium, however, no observed

Table 2. Average Flow (L/min) and Loading (GPD) For Parameters For The WTSs.

WTS	Flow (L/min)	Iron GPD	Aluminum GPD	Manganese GPD	Acidity GPD
K2	22.7	2,340	18.4	302	2,670
K3	50.7	1,540	120	1,270	4,530
JEEC	129	3,740	3,284	1,120	45,470
CUC1	66.6	2620	234	94.3	7,520
CUC2	7.9	327	4.3	20.8	964
CUC3	13.6	191	78.2	88.6	2,010

increases in hardness were observed across any WTS. The absence of hardness increases may have been due to interferences of divalent and trivalent metals (e.g., iron and aluminum) that are well documented on the colorimetric hardness test used in this study (APHA 1991).

Loading and Removal Rates

The monitoring program was designed to evaluate parameters loadings and removals of each WTS and intermediate cells. WTS loadings, in grams per day (g/d), were determined by multiplying sampling date flow, in liters per minute (L/min), by influent concentration. Sampling date loadings were used to determine an average loading over the sampling program. Removal rates, also in g/d, were determined by subtracting sampling date effluent loading from influent loading, and were then used to determine the average removal rates. Unit area removal rates, in grams per day per square meter (g/d/m^2), were determined by dividing removal rate (g/d) by the surveyed WTS and cell sizes. Acidity removal and alkalinity production rates were combined to provide the acidity removal rate.

The average influent flows for the WTSs and the loading for selected parameters received by each WTS are summarized in table 2. Flows received by the WTSs were variable ranging from 7.9 L/min (2.1 gal/min) at the CUC2 to 129.1 L/min (34.1 gal/min) at the JEEC. Average acidity loading tended to correlate well with the flow received by each WTS. The JEEC received the highest acidity loading of 45,470 g/d and the CUC2 received the lowest acidity loading of 964 g/d. Average iron loading did not correlate as well with flow as did acidity. The JEEC WTS, which received the highest AMD flow, also received the highest iron loading of 3,740 g/d, but several iron loadings received by the WTSs (K2 and CUC3) were influenced by concentration. Aluminum and manganese loadings did not correlate with flow as was observed for iron.

Table 3 summarizes average removal rates and unit area removal rates for each parameter in each WTS. Removal rates for iron ranged from 102.5 g/d at the CUC3 to 2,260 g/d at the K2. The average influent iron concentration for each of these wetlands (table 1), which were 10.6 and 98.3 mg/L, suggest that iron removal may be influenced by influent iron concentrations. This is further supported by examination of removal results from duplicate sequential units within the K2 WTS. The iron loading to cell 1 averaged 1,170 g/d and cell 2 averaged 330 g/d, with corresponding removal rates of 840 g/d and 170 g/d, respectively. Further, iron removal at two WTSs (K3 and CUC2), which had similar average influent iron (41.0 and 35.2 mg/L), differed by almost an order of magnitude (table 3). Examination of average influent pH (5.20 and 3.27, respectively) and influent ferrous iron (37.5 and 17.3 mg/L, respectively) suggest that iron removal may be related to other influent water quality conditions.

Unit area removal rates for iron ranged from 0.22 to 6.47 g/d/m^2 at the WTSs. The two wetlands with the highest unit area removal rates, Canoe Creek K2 (2.37 g/d/m^2) and K3 (6.47 g/d/m^2), also had the highest influent pH values of 4.64 and 5.20, respectively. The highest iron removal rate was from K3, which also had one of the highest influent concentrations (41 mg/L); the lowest removal rate

Table 3. Average Removal Rates in GPD and GDM For Parameters For The WTSs.

WTS	Iron		Aluminum		Manganese		Acidity	
	GPD	GDM	GPD	GDM	GPD	GDM	GPD	GDM
K2	2,260	2.37	2.21	0.002	-12.9	-0.01	4,400	4.62
K3	1,450	6.47	-73.0	-0.33	58.6	0.26	2110	9.45
JEEC	1,540	1.33	952.	0.82	74.5	0.06	20,600	17.7
CUC1	1,280	0.95	45.7	0.03	-0.81	-0.001	2,626	1.95
CUC2	188	2.05	0.09	0.001	1.47	0.02	367	3.99
CUC3	102	0.22	33.4	0.07	16.2	0.01	2,880	6.27

was from CUC3, which had the lowest influent concentration (10.6 mg/L). Therefore, the unit area removal rates for iron also suggest that iron removal is dependent on influent water quality.

Average removal rates for aluminum and manganese were more variable than iron removal rates. Aluminum removal rates ranged from -73.0 g/d at the K3, which indicates aluminum was added by the WTS, to 952 g/d at the JEEC. Unit area removal rates for aluminum ranged from -0.33 g/d/m^2 at the K3 to 0.83 g/d/m^2 at the JEEC. The remaining area rates were approximately zero. Manganese also had negative removal rates at several WTS including -12.9 g/d at the K2 and -0.81 g/d at the CUC1. The highest removal rate for manganese of 74.3 g/d occurred across the JEEC. The majority of unit area manganese removal rates were approximately zero, except for a rate of 0.26 g/d/m^2 measured at the K3 WTS.

Average acidity removal rates ranged from a low of 367 g/d in the CUC2, the smallest WTS, to a high of 20,600 g/d in the JEEC, the second largest WTS. This suggests that removal rates may be dependent upon WTS size. The largest WTS (CUC1) did not have the largest removal rate; however, this WTS had a large open water area at the beginning and no barriers to prevent short circuiting of the WTS. This size-dependent relationship of acidity removal is further supported by acidity removal rates from two different size, sequential cells from the JEEC WTS and two similar-size, sequential cells in the K2 WTS. Cell 2 (259 m^2) in the JEEC WTS had a removal rate of 2,972 g/d and Cell 3 (344 m^2) had a correspondingly greater removal rate 3,628 g/d. Cell 2 and 3 in the K2 WTS had comparable treatment areas of 187 m^2 and 181 m^2 with similar removal rates of 1,316 g/d and 1,119 g/d.

Unit area removal rates were fairly consistent in the WTSs, ranging from a low of 1.95 g/d/m^2 at the CUC1 to 17.7 g/d/m^2 at the JEEC. The low rate at the CUC1 may have been due to poor use of the treatment area as previously mentioned. This poor acidity removal in deep open water areas is further substantiated by the low acidity removal rate of 0.1 g/d/m^2 from the open water sediment pond at the K2 WTS. The high rate for the JEEC may have been due to modifications (see WTS Design section) at the JEEC that were made in an attempt to improve treatment effectiveness, and suggests that modifications were, in part, beneficial. Without these two WTS unit area removal rates, the range decreases to a low of 3.99 g/d/m^2 and a high of 9.45 g/d/m^2. In addition, cell 2 and cell 3 from the JEEC, which had different treatment areas, had very similar unit area removal rates of 11.5 g/d/m^2 and 10.6 g/d/m^2, respectively. The similar sized cells (cell 1 and 2) from the K2 WTS also had similar unit area removal rates of 7.0 g/d/m^2 and 6.2 g/d/m^2, respectively. These results from the JEEC and K2 WTSs also suggest that there is no effect of influent acidity concentration or any other water quality parameter on acidity removal.

Design Criteria

The remaining goal of the DER project was to develop design guidelines for future WTS projects. Removal efficiencies in the WTSs varied owing to differences in design, flow, and AMD loading of parameters. Total iron removal rates for the systems were inconsistent and appear to be affected by influent water quality (e.g., influent iron concentration, fraction of ferrous, and pH). In addition, the removal rates from the WTSs suggest iron removal rates (g/d) are not a function of size; therefore, no size independent unit area removal rate (g/d/m^2) can be determined. As was found for iron removal rates, both aluminum and manganese removal rates were inconsistent, contained negative rates, and varied by greater than two orders of magnitude; therefore, these two parameters would not produce adequate estimates on which to base WTS design criteria.

Although no treatment goals were established for acidity, this water quality parameter was included in the design analysis, due to the relationship between this parameter and hydrolyzable metals. Total acidity is defined as the sum of hydrolyzable metals (e.g., ferric iron and aluminum), mineral acidity (e.g., sulfuric acid), hydrogen ions (i.e., pH), and carbonate acidity (Stumm and Morgan 1981). Effluent acidity and total iron data for the CUC1 (r^2=68%), CUC2 (r^2=28%), JEEC (r^2=81%), and K2 (r^2=20%) were found to be significantly correlated. This suggests that iron and acidity removal are dependent, and acidity removal should have a corresponding reduction of metals (e.g., iron and aluminum).

WTS removal rates for acidity ranged from 367 to 20,600 g/d and appear to correlate with the size of the WTS. Further, the results from the individual cells in K2 (cell 1 and cell 2) and the JEEC (cell 2 and cell 3) WTS suggest removal rates, based on unit area (i.e., g/d/m^2), are independent of WTS size and influent quality. Finally, unit area acidity removal rate differences may be attributed to WTS design, as found at the CUC1 (1.95 g/d/m^2) and JEEC WTS (17.7 g/d/m^2).

Due to water quality independence, size independence, and its relationship to WTS design, the acidity unit area removal rate (g/d/m^2) was selected as the parameter for sizing WTSs. Further, complete removal of acidity would likely decrease the majority of iron (ferric) and aluminum, which both have pH dependent solubility. In addition, 100% removal of acidity would have the added benefit of increasing effluent pH. Only manganese would not be addressed by acidity removal due to the presence of reduced manganese (Mn^{+2}), which is not subject to hydrolysis. The oxidized form of manganese (Mn^{+4}) is subject to hydrolysis; however, manganese oxidation is not likely at the low redox conditions that normally occur within a compost WTS.

A mean acidity unit area removal rate of 8.2 g/d/m^2 was estimated from WTS (K3, CUC2 and CUC3 WTS) and individual treatment cell (K2 and JEEC WTS) removal rates. Rates not used in the average included the CUC1 WTS and the K2 sediment pond (because of the large amount of open water), cell 3 of the K2 WTS (because of the seep), and cell 1 and 4 of the JEEC WTS (because of the unique modifications made to the two cells). The 95% confidence limit of this mean is 6 g/d/m^2 to 9.4 g/d/m^2. The lower limit of 6 g/d/m^2 is a conservative value that should incorporate variability in site conditions, vegetation, and mushroom compost composition and is recommended as the design criterion for future WTSs that incorporate a surface flow design that utilizes only compost as a substrate material.

Higher acidity removal rate design criteria may be warranted if the WTS incorporates unique design features other than the standard design used in this project. A single unit in the K2 WTS (cell 4) contained limestone underneath the mushroom compost and was found to have a slightly higher removal rate of 10 g/d/m^2. WTS design that incorporates limestone troughs, as was attempted in two cells of the JEEC WTS, may warrant higher design criteria in the 15 to 20 g/d/m^2 range. A recent initial investigation of a small-scale WTS that incorporated a subsurface flow design, based on the JEEC attempts, yielded acidity removal rates in the 25 to 50 g/d/m^2 range (Dietz et al. 1993)

Recommendations

WTS size (compost wetland) should be based on a conservative acidity loading that considers variability of influent flow and acidity (e.g., 95% upper confidence limit of mean acidity loading data) and uses a conservative removal rate (e.g., 6 g/d/m2). In addition, WTS sizing should be based on complete removal of acidity plus the production of 20 to 40 mg/L (as $CaCO_3$) of alkalinity (Dietz and Stidinger 1993). (Examples of WTS design calculations are contained in appendix D of the "Evaluation of Wetlands Constructed for the Treatment of Acidic Mine Drainage")

Once the total WTS size has been determined, the total area should be divided between two and four treatment units to prevent hydraulic short circuiting. In addition, when possible, the units should be rectangular with open channels for the influent and effluent. Channels should be located at opposite ends of the unit to provide additional protection against short circuiting of the system. The wetlands should contain a minimum of 0.3 m (1 ft) of compost planted with cattails (*Typha lattifolia*) or some other indigenous wetland vegetation. As previously discussed, limestone placed beneath the compost or some type of limestone-subsurface flow system (e.g., JEEC WTS) may be warranted in future designs to improve treatment effectiveness and/or reduce overall WTS surface area. Additional benefit may be gained by placement of a detention and/or open-water basin prior to the WTS, providing more consistent treatment by reducing loading and flow variability and reducing high ferrous iron (>10 mg/L) when in combination with a high pH (>5).

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