WETLAND SIZING, DESIGN, AND TREATMENT EFFECTIVENESS FOR COAL MINE DRAINAGE [1]

by

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Abstract. Constructed wetlands are a proven means of treating and improving the quality of mine drainage, but they do so with varying degrees of effectiveness. The area and/or volume of constructed wetlands may influence effluent quality as much as the vegetative make-up of these systems and therefore, becomes a primary design consideration. Accurate flow data is paramount in determining wetland sizing requirements and ultimately in treatment efficiency, and should become a routine part of any wetland monitoring program. Evidence exists that seasonal variations occur for iron removal in constructed wetlands, but these variations may be influenced as much by "total loads in" as by treatment area and biological efficiency. Furthermore, there is an inverse relationship between the percent of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}) in the total iron load and the removal efficiency of total iron in the wetland, indicating that the actual flow regime in the system is as important as area and vegetation. The oxidation and removal of iron from mine drainage often results in decreased pH values. However, iron removal and pH increases have been demonstrated in constructed wetlands without the use of alkaline substrates.

Additional key words: Mineral loading, seasonal efficiency, flow regime.

Introduction

Constructed wetlands are a proven means of treating and improving the quality of mine drainage, but they do so with varying degrees of effectiveness. There are numerous reasons as to why constructed wetlands vary in treatment effectiveness, but one important consideration relates to the sizing of such systems. That is, "how large does a wetland need to be to effectively treat a given mine discharge?" Iron loads are given prime consideration in this discussion of sizing because of the various implications iron concentrations have on the entire functioning of wetland treatment systems.

The presence of iron in discharges can inhibit the removal of other minerals from those discharges in both constructed and natural wetlands (Kepler 1986; Stevens, et al. 1989). Additionally, the presence and/or chemical state of iron will be shown to be critical in the complete wetland treatment system; i.e., one that is designed to increase pH and alkalinity values as well as remove iron and acidity.

Study Area

The Site 1 wetland is located in Venango County, PA and was constructed in October of 1987. The wetland is divided into two parallel series of four ponds each, with a common initial collection pond (Table 1). An attempt was made to provide equal flows to both series over the course of the study, although variations did occur. However, the data are presented in loadings, which does allow for comparisons of iron removal between the parallel channels. The mean total flow for these months was 106 L/min, with a range of 77-143 L/min.

The drainage at Site 1 is associated with the Lower Kittanning Coal Seam and has been flowing unabated from an abandoned drift mine opening since at least 1940. The sample period was November 1987 through March 1989 (May and June, 1988 are discussed separately because of anomalies in the data resulting from physical alterations to the wetland during this time period).

The Site 2 wetland is located in Clarion County, PA and was constructed in August, 1988 through funding from the Pennsylvania Department of Environmental Resources, Bureau of Abandoned Mine Reclamation (in conjunction with EADS acting as biological consultant). The quality of this mine discharge is a reflection of the overburden associated with the Upper Clarion Coal Seam which was surface mined at this site in the early 1970's. Site 2 is characterized by an open water pond covering roughly 125 m^2 (depth = 1.5m), followed by a series of four *Typha* dominated cells, each measuring approximately 6m by 30m (180m^2 each).

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Table1. Site 1: Individual pond surface areas and volumes.

Configuration*	Surface Area (m^2)	Volume (L)
TTAA		
T1	42	15,897
T2	49	10,087
A1	67	45,420
A2	63	39,080
Total	221	110,484
AATT		
A1	80	47,483
A2	60	39,440
T1	41	11,241
T2	49	11,241
Total	230	109,404
Initial Pond	102	53,368

*Configuration refers to planting strategy in parallel systems. T = *Typha*, A = Algae

Flows were inadvertently not monitored at this site during the initial months of collection, but were determined for the latter half of the existing analyses. This oversight is typical of many monitoring programs and has been taken into consideration in the ensuing discussions. Accurate flow data is paramount in the determination of wetland treatment efficiency and ultimately sizing requirements, and should become a routine part of any wetland monitoring program. The sample period for this discussion is August 1988 through September 1989, with the mean total flow for the measured months being approximately 12 L/min, at a range of 2 to 50 L/min. A characterization of the quality of the two source discharges is given in Table 2.

The predominant planting (excluding the noted algal ponds) in the two wetlands was *Typha latifolia* . Both wetlands were excavated and sealed with on-site clay and incorporated 30cm of composted manures and hay as substrate in the areas dominated by the *Typha* plantings. The *Typha* were planted as core samples on roughly 0.6m centers, but spread to essentially one hundred percent surface coverage by the end of the first complete growing season. Core samples refer to hand dug, intact rhizome/soil units.

Methods

The two principle wetlands discussed in this paper have at a minimum, fourteen months of weekly water analyses collected from various points within the systems. The data are discussed mainly in terms of total mineral loadings as opposed to concentrations; therefore, flow data plays a large role in these evaluations. Loadings are calculated by multiplying concentration data (mg/L) by flows (L/min) by a conversion factor (1.44) = gms/day. The loading values will be adjusted to reflect wetland sizing by dividing gms/day by area (m^2). The resultant values therefore indicate gms iron/day/m^2 and for brevity will be given as "gdm." The importance of evaluating wetland performance by this method is illustrated in the following two examples.

First, the importance of loading data as opposed to concentration data is shown in a comparison of two water collection points, one showing an iron concentration of 1mg/L at a flow of 100L/min and the other a concentration of 100mg/L at a flow of 1L/min. Any conclusions based on the loading data would indicate identical values. The concentration values alone could easily lead to erroneous conclusions.

In like fashion, the importance of area in treatment evaluations may be seen in the comparison of two wetlands that remove equal amounts of iron from their respective flows, eg., 100gms/day. If one of these wetlands encompasses twice the treatment area of the other, say 1,000m^2 versus 500m^2, than the smaller system is twice as effective in removing iron as is the larger wetland. However, there are additional factors that must be considered in regards to both loading and sizing evaluations in any wetland treatment discussion that will be subsequently examined in this paper.

Flows were calculated by means of a portable cutthroat flume and by timing with a bucket and stopwatch. Site 1 water samples were collected and analyzed by the EADS Group using standard methods (e.g. American Public Health Association), while the vast majority of data from Site 2 was taken from samples collected and analyzed by PA D.E.R. personnel. Monitoring points were established at AMD source and final wetland discharge points and at the distinct inflow/outflow points of the individual sections of the entire wetland systems. Typical analyses inclued pH, alkalinity, acidity, conductivity, total and ferrous iron, total and dissolved manganese, aluminum, and sulfate. The water analyses were examined and are discussed as a whole and by month.

Results

The total iron removal rates per pond in gdm for Site 1 are shown in Table 3. The monthly removal rates for total iron from the first two sets of opposite ponds at site 1 are graphically depicted in Figures 1 and 2. The arrangement of ponds at Site 1 was such that the order of planting was reversed in the opposite channels. This design allowed for comparisons to be made as to the effectiveness of both vegetative make-up and area/volume considerations in iron removal.

The *Typha* dominated ponds at this site removed more iron from the flows on a per area basis than did their counterpart algal ponds. This removal translates into an even greater efficiency on a per volume basis since the algal ponds were built with a greater depth than the *Typha* ponds. Ponds T1 and T2 in the TTAA series showed the greatest, consistent propensity toward iron removal in the wetland, while three of the algal ponds and the two remaining *Typha* ponds displayed relatively consistent removal rates (Table 3). The final algal pond in the TTAA series consistently displayed

Table 2. Mean source quality of AMD at Sites 1 and 2*.

	pH	Alkalinity	Acidity	Sulfate	Fe2+	Fe(tot)	Mn	Al
site 1	5.5	50	250	2100	35	90	50	1
site 2	5.7	28	145	970	135	180	20	<1

*Alkalinity and acidity = CaCO^3 equivalent, others in mg/L

Table 3. Site 1: Total iron removal rates per pond in gdm.

Configuration	gdm (mean)	gdm (range)
TTAA		
T1	25.3	8-53
T2	26.1	7-68
A1	11.1	5-28
AATT		
A1	16.5	1-35
A2	14.7	5-35
T1	13.3	4-28
T2	14.2	1-31

Figure 1. Total iron removal in gdm, AATT A1 vs. TTAA T1.
November 1987 = 1 through March 1989 = 17

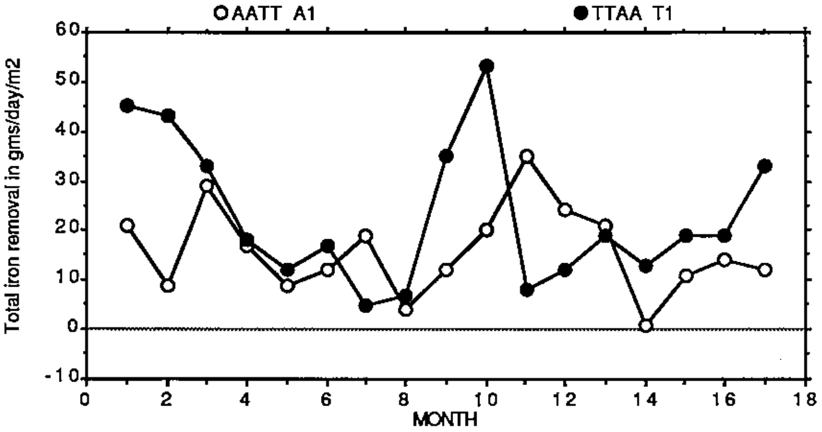
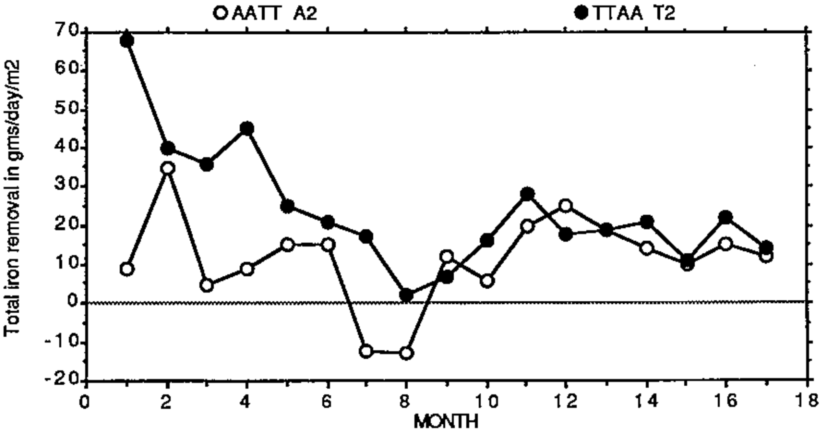


Figure 2. Total iron removal in gdm, AATT A2 vs. TTAA T2.
November 1987 = 1 through March 1989 = 17



greater effluent iron values than influent values. This finding resulted from an inability to collect "clean" samples because of concentrated iron precipitates at the sampling location and does not reflect the true treatment efficiency in this pond. TTAA A2 is not included in subsequent calculations or discussions.

There is a positive relationship between total inflow iron loads and iron removed in gdm in the TTAA T1, T2, and A1 ponds and pond T2 of the AATT series. The *Typha* dominated areas in particular appear to be more effective at removing iron at higher loads than at lower loading rates. The Site 2 data further suggest that iron is more effectively precipitated in large versus small quantities. The initial open water pond at Site 2 was designed to act as a sedimentation basin and as a retention pond for iron removal, because the relatively low flows and high pH values found here lent well to this design. The mean removal rates (gdm) on a monthly basis for this pond are shown in Figure 3, with the actual mean removal for the extent of monitoring being 15.8 gdm (range = 4.4 - 81.6). The high value occurred in May of 1989 during the highest measured flow value period for this system. The mean removal rate is similar to much of the Site 1 data, but is rather high when compared with the next two cells in series, where mean removal rates equalled 1.4 and 0.7 gdm respectively (Figure 3).

Seasonally, wetlands are generally considered to be less effective regarding treatment during the colder months, since biological functions slow with decreasing temperatures. Consideration should be given to whether there is an actual decrease in treatment effectiveness during the winter, or if effluent values are more of a reflection of influent loadings as described above. For instance, it was noted that at both sites, removal rates correlated positively with loadings at the source. Iron removal at Site 2 proved to be most effective during May, June, and July (the three highest flow periods) and lowest during February, which was the lowest flow period. These months also represented the respective extremes in actual iron loadings. Seasonal findings are limited in this paper because both wetlands were relegated to essentially one season's worth of data, but an additional Site 2 trend should be noted. The iron removal rate in December was slightly greater than that in August (Figure 3), a contradiction to "expected" seasonal wetland perfomance, but December's source loading was also greater than in August.

The state of iron, ferrous (Fe^{2+}) or ferric (Fe^{3+}) also plays a role in iron removal efficiency in wetlands. The mentioned anomolous May and June data for Site 1 resulted from physical alterations to the wetland that routed the mine drainage beneath the substrate (rather than across the substrate) of the initial collection pond. During this period, anaerobic conditions in the substrate tended to convert the Fe^{3+} to Fe^{2+} in the mine flow, essentially shuting down iron removal and in some instances actually leading to increases in total iron under these conditions. Fe^{2+} constituted a very minor portion of the total iron load at the discharge of this wetland during the other sample months (under aerobic conditions) and the wetland was extremely effective at removing iron from the drainage.

Site 2 characterizes a "complete" wetland as noted in the introduction, in that iron removal and pH increases are shown in the same wetland without the use of a limestone substrate (Table 4). The compost utilized as substrate in this wetland has an approximate neutralization potential of 3.5% $CaCO_3$ equivalent which cannot account for the changes seen in pH and alkalinity values. The results in Table 4 can be attributed to the design of the system which utilizes an initial, iron oxidizing pond followed by subsurface flows and anaerobic conditions in cells 1 and 2. Sulfate reducing bacteria have demonstrated the ability to cause dramatic changes in constructed wetland substrate water quality (Hedin et al. 1988) and likely are responsible for the quality improvements shown here. Further discussions concerning the effectiveness of this design will be presented in future preceedings, but at this time it is important to document that the Site 2 wetland has been consistently functioning at the level shown in Table 4 for 14 months.

Discussion

The above results indicate that wetland sizing criteria are of little consequence if regard is not given to the relationship between pH, Fe^{2+}, Fe^{3+}, alkalinity, acidity, and sulfate. Of necessity, there is a maximum iron load where removal efficiency decreases, and below that maximum value, removal rates must be limited by influent values; i.e., there is a greater opportunity to precipitate more iron at a higher loading than at a lower loading value. A wetland cannot remove 25 gdm if the source value is less than 25gms. Flow manipulation can lead to dominant aerobic or anaerobic conditions in constructed wetlands. Both conditions coexist in any wetland, constructed or natural, and probably play a critical role in both the rapid precipitation of $Fe(OH)_3$ and in the decreasing efficiency of iron removal with decreasing loads in the later stages of wetland treatment.

Typically, Fe^{2+} makes up the vast majority of the total iron load at the actual source of mine drainage. Exposure to the atmosphere, retention time, and a moderately high pH (as seen at Site 2, pH = 5.7) leads to the rapid oxidation and precipitation of iron as an oxyhydroxide ($Fe(OH)_3$). Particles of $Fe(OH)_3$ are commonly positively charged, and upon contact with negatively charged clay particles or organic colloids, tend to become neutralized. These uncharged aggregates can then join to form rapidly settling precipitates (Wetzel 1975) which are generally conspicuous in wetlands receiving mine drainage. The combination of high concentrations of organic matter found in *Typha* -dominated areas, and high iron loads, readily encourages a system where large aggregates of iron floc form and precipitate. This phenomenon was seen in the Site 1 TTAA/AATT comparisons. At lower loading rates, the potential for rapidly combining $Fe(OH)_3$ precipitates to form decreases.

Most remaining iron at the discharge point of these wetlands is in the Fe^{2+} state. The first pond (125m^2) in the Site 2 system removes an average of almost 2,000 gms/day of iron from the drainage, but the following two cells in total (totalling 360m^2) remove only an additional average of 250 gms/day of iron from the flows. Within the substrate where high organic matter exists, and at the sediment-water interface of wetlands, reducing conditions prevail and tend to control the quality of effluent in the wetland. Ferrous iron can form a strong soluble complex with dissolved organic matter (Gjessing 1964) and therefore maintain a measurable level of iron in even a typical (oxidizing) constructed wetland. This reaction is even more pronounced in subsurface flow designs, and may be one reason why little iron was removed under anaerobic connditions as noted in the May and June data at Site 1.

Seasonally, biological treatment efficiency decreases with decreasing temperatures. However, if the primary removal of iron is based on oxidation (with precipitation accelerated by the presence of organic matter) winter wetland efficiency should not decrease to any great degree when compared to summer values. Oxygen solubility increases with decreasing temperatures and organic matter is in abundance in the fall and winter in a system dominated by persistent emergents (*Typha*). The finding here that seasonal trends are not evident and in fact that some winter removal rates exceed summer removal rates, adds credence to the argument that colder temperatures may not significantly affect wetland iron removal efficiency.

Figure 3. Total iron removed in gdm, Site 2.
August 1988 = 1 through September 1989 = 14

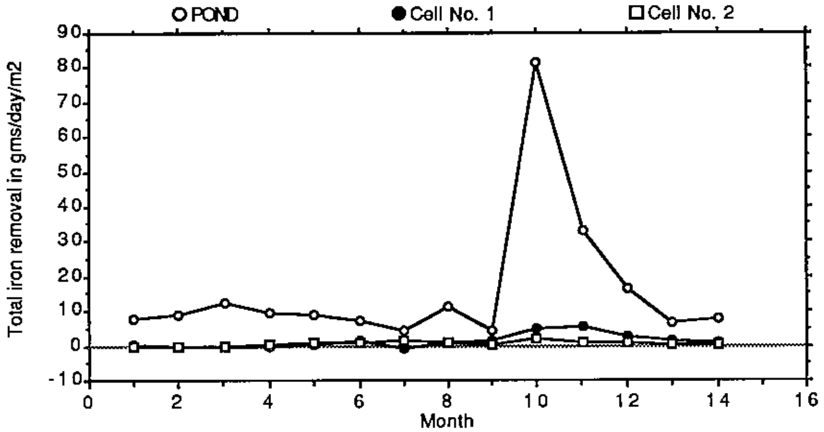


Table 4. Typical water quality at Site 2.

	pH	Alkalinity*	Acidity*	Sulfate	Fe2+	Fe(tot)	Mn	Al
source	5.7	28	145	970	135	180	20	<1
pond outlet	3.0	0	125	825	32	34	19	<1
cell 1 outlet	6.7	85	0	650	12	15	18	<1
cell 2 outlet	6.9	145	0	580	6	8	18	<1

*Alkalinity and acidity = $CaCO_3$ equivalent, others in mg/L

On an average annual basis, it appears that these wetlands are capable of removing approximately 15 gdm of iron. While this value may eventually be supported, at this time it should at best be used as a general "rule-of-thumb" in design. Accurate, seasonal baseline data of a mine discharge regarding both quality and quantity is critical if any sizing criteria at all is to be employed. Maximum iron loads should be multiplied by a margin of safety (eg., 25%) in the designing of treatment wetlands.

Conclusions

Aristotle once said that "We cannot expect a degree of accuracy that is not inherent to our subject." Unfortunately, this statement is presently appropriate to definitive sizing criteria for constructed wetlands. The presented information has proven valuable in designing wetlands to treat AMD, but is little more than a starting point in the development of a "guaranteed" design manual. There are numerous avenues of research that are required to complement and confirm the data presented here.

Generally, seasonal wetland performance requires more research, with an excellent starting point being the monitoring of substrate temperature. Monitoring substrate temperature is especially important in understanding the mechanisms of treatment in designed, reducing wetlands that depend on bacteria for their effectiveness. Biomass balances within the wetland system must also be considered if treatment is based on a bacterially mediated system. High density stands of emergents such as *Typha* are commonly used in constructed wetlands and probably provide adequate organic material to the wetlands on a year-round basis. Low pH values in mine drainage usually negatively affect iron removal and should also be given more consideration in future work. The hypothesis that iron removal efficiency is more of a function of loading than seasonal temperature variations need also be examined.

It must also be stated that all of these concerns approach the aspect of design and sizing criteria from a rather simplistic approach. It is much more likely that there are significant interactions between numerous considerations that influence the efficiency of a wetland treatment system. If accurate design models are to be developed, they will be multidimensional and will address the issue of substrate depth equally with source iron loads. An example of this complexity follows.

Although data must be presented in terms of loadings and/or gdm for purposes of comparison, simple loading to loading comparisons may also be misleading. The earlier example of 1mg/L of iron at a flow of 100L/min and a second flow of 1L/min with an iron concentration of 100mg/L led to identical loads and reportedly identical conclusions. However, experience has shown that this discrepancy between flows would require two distinct wetland designs. The lesser flow/higher iron discharge could be treated more efficiently and with less treatment area than the higher flow/lower iron discharge regardless of equal loading values primarily because of the ease of manipulating smaller volumes of water.

These statements are not intended to discourage those looking for a definitive design manual. The effective treatment of AMD in constructed wetlands is consistently improving. The mere fact that the above questions and considerations are being raised is proof enough that the field of wetland treatment has progressed significantly from questioning simply "how to remove iron from AMD."

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