SIZING AND PERFORMANCE OF CONSTRUCTED WETLANDS: CASE STUDIES [1]

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Abstract: Iron removal in three Pennsylvania wetlands constructed to treat acid mine drainage was evaluated. All wetlands were constructed with a mushroom compost substrate and were planted with Typha spp. Performance was evaluated by calculating area-adjusted iron loadings and removals as Fe g day^{-1} m^{-2} (gdm). An initial model of the iron removal capabilities of constructed wetlands was also evaluated. Relationships between pH, concentration, flow, loading and removal were considered. At the Somerset Site (avg. influent pH=4.0), influent iron loading, which was primarily a function of concentration, was considerably more variable than iron removal. The relationship between the two appeared asymptotic, with removal being independent at loadings above 15 gdm (avg. removal = 10.6 gdm) and averaging 54% of loading at loadings less than 15 gdm. Conversely, at the Latrobe Site (avg. influent pH=3.0), variation in iron loading was primarily a consequence of flow variation. Removal averaged 2.7 gdm at flows > 100 L min^{-1} and 4.3 gdm when flow < 100 L min^{-1}. The overall average removal was 3.6 gdm. A significant relationship between loading and removal was not found. At the Friendship Hill Wetland, influent pH was 2.7, and iron removal averaged 3.3 gdm. The narrow range of loadings at this site prevented detailed analysis of loading:removal relationships. Overall, these data were used to develop preliminary wetland sizing criteria based upon iron loadings. In situations where mine drainage has flow > 50 L min^{-1} and iron concentration > 50 mg L^{-1}, loading-based criteria result in significantly larger wetlands than conventional flow-based criteria.

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Introduction

Constructed wetland technology has advanced considerably in recent years, but sizing criteria have evolved very little from initial suggestions that 5.0-15.0 m^2 of wetland were needed for each liter per minute (L min^{-1}) of contaminated flow (Kleinmann et al . 1986, Girts et al .

1987). Although this sizing standard was only intended for drainage with flow less than 40 L min^{-1}, pH greater than 4 and iron concentration less than 50 mg L^{-1} , it has been applied to systems that receive much higher flows and poorer water quality. Many of these systems do not perform satisfactorily, probably in part because they are undersized. A better sizing standard that incorporates contaminant concentrations as well as flow is needed.

The belief that a "correct" sizing methodology exists derives from an assumption that a square meter of wetland can remove a predictable amount of contaminant in a day's operation. This sizing hypothesis can be evaluated empirically by analyzing iron-removal by existing constructed wetlands. In this paper, the iron-removal capabilities of three constructed wetland systems are evaluated. We focus on iron because it is the principal metal contaminant in coal mine drainage and appears, thus far, to be most suited to wetland treatment.

Evaluation of Wetland Performance

To make reliable evaluations of wetland performance, a measure should be used that allows comparison of contaminant removal for systems of different sizes that receive drainage with different flow rates and chemical compositions. In the past, concentration efficiency (CE%) has been a common measure of performance (Girts et al. 1987, Stark et al. 1988). For iron (Fe) the calculation is:

$$CE\% = \frac{Fe\ (mg\ L^{-1})_{in} - Fe\ (mg\ L^{-1})_{out}}{Fe\ (mg\ L^{-1})_{in}} \times 100 \quad (1)$$

In many cases, this is a poor measure of performance. Comparisons of iron removal efficiencies for different wetland systems fail to provide sizing insights because the calculations do not include any measure of contaminant masses or wetland size.

A better evaluation procedure involves several components. First, the daily mass of iron at each sampling station must be calculated:

$$Fe\ (g\ day^{-1}) = 1.44 \times flow\ (L\ min^{-1}) \times Fe\ (mg\ L^{-1}) \quad (2)$$

(where 1.44 is the adjustment factor needed to convert minutes to days [1,440] and milligrams to grams [0.001]). This value, grams of iron per day, is commonly referred to as the iron "loading." The amount of iron removed by the wetland between two sampling stations is calculated by comparing iron loadings at the two points.

$$Fe\ (g\ day^{-1})_{rem} = Fe\ (g\ day^{-1})_{in} - Fe\ (g\ day^{-1})_{out} \quad (3)$$

Conventionally, a comparison of the influent and the final effluent station is made to determine the effect of the whole wetland on iron loading. However, when additional water samples are collected, the iron removed by individual cells can be calculated.

The second calculation involves adjusting the iron loading for wetland size. For inlet stations, the amount of the daily iron load apportioned to each square meter of downflow wetland can be estimated by:

$$Fe\ (g\ day^{-1}\ m^{-2}) = \frac{Fe\ (g\ day^{-1})_{in}}{area\ (m^2)} \qquad (4)$$

An estimate of the amount of iron removed by each square meter of wetland between two sampling points can be calculated:

$$Fe\ (g\ day^{-1}\ m^{-2})_{rem} = \frac{Fe\ (g\ day^{-1})_{in} - Fe\ (g\ day^{-1})_{out}}{area\ (m^2)} \qquad (5)$$

These values will be referred to as "area-adjusted." The units, grams of iron per day per m^2 of wetland, will be referred to as "gdm." We will focus in this paper on 1) area-adjusted iron loading, which is the average amount of iron that each square meter of wetland is exposed to in one day, and 2) area-adjusted iron removal, which is the average amount of iron removed by each square meter of wetland per day.

To illustrate the use of iron loading and area-adjusted iron loading estimates, consider the hypothetical data presented in Table 1. In Systems A and B, changes in iron concentrations are the same (60 mg L^{-1}), but because system B receives four times more flow and thus higher iron loading, it actually removes four times more iron from the water (see rem in g day^{-1}). The concentration efficiencies of the two wetlands are equivalent, but masses of iron removed are quite different.

Hypothetical data are shown for System C for three sampling dates on which flow rates and influent iron concentrations vary. On the first date (Cl), the wetland removes all of the iron that it receives. On the next two dates (C2 and C3), iron loadings are higher and the wetland effluent contains iron. From an efficiency standpoint, performance is best on the first date and worst on the third date. But from an iron-removal perspective, the system is removing the least amount of iron on the first date. On the second and third dates the wetland removes similar amounts of iron (2880 and 3024 g day^{-1}). Variation in effluent chemistry results, not from changes in the wetland's iron-removal performance, but from variation in influent iron loading.

Table 1.-- Hypothetical Wetland Data and Performance

wet-land	size	flow	Fe (mg L^{-1})			Fe (g day^{-1})			Fe (g day^{-1} m^{-2})		
	m^2	L min^{-1}	in	out	%rem	in	out	rem	in	out	rem
A	400	10	100	40	60	1440	576	864	3.6	1.4	2.2
B	400	40	100	40	60	5760	2304	3456	14.4	5.8	8.6
C1	500	30	40	<1	99	1728	<40	1688	3.5	<.1	3.4
C2	500	80	35	10	71	4032	1152	2880	8.1	2.3	5.8
C3	500	150	30	16	47	6480	3456	3024	13.0	6.9	6.1
D	750	50	100	25	75	7200	1800	5400	9.6	2.4	7.2

Lastly, consider a comparison o wetland systems of different size. System D removes more iron than any wetland considered (5400 g day^{-1}), but it is also larger. One would expect, all other factors being equal, that a larger wetland would remove more iron. When wetland area is incorporated into the measure by calculating area-adjusted iron removal values, System B emerges as the most effective wetland considered (see removal gdm values).

Iron Removal Model

In addition to evaluating iron removal on a whole wetland basis, we analyzed the relationship between area-adjusted iron loading and removal for individual wetland cells. The objective of this analysis was to initiate the development of a model of iron removal in constructed wetlands. Figure 1 is a plot of loading and removal for a hypothetical model wetland. The shape of the plot results from an assumption that iron removal processes are limited to a maximum rate (point A"). When inflow loading is less than the maximum rate, 100% removal can occur (removal = loading). The low flow data from hypothetical wetland C1 plots on this line. At inflow loads greater than the maximum rate (point A'), constant iron removal occurs. The high flow data from wetland C (C2 and C3) fall near this line.

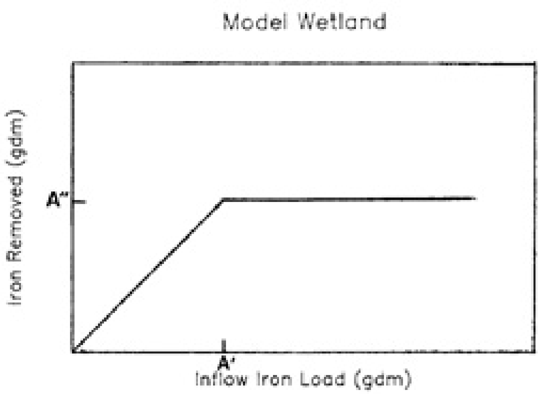

Figure 1. Hypothetical relationship between area-adjusted iron loading and area-adjusted iron removal in a constructed wetland.

One goal of this paper is to determine how accurately the performance of constructed wetlands is represented by this model. We were also interested in determining whether area-adjusted iron removal rates differed between wetlands and, if so, whether this variation could be attributed to particular characteristics of the influent water (e.g. pH, Eh, [Fe]).

Selection of Study Wetlands

Study wetlands must satisfy some basic standards if comparisons of iron removal are to provide insights into system performance. The wetlands being evaluated and compared must be built using similar designs and materials. In northern Appalachia, the "standard" wetland consists of 30-45 cm of compost substrate planted with cattails (Typha spp.). Water in the standard wetlands flows primarily by surface routes. The study systems must have distinct inlet and outlet stations where accurate flow measurements and representative samples can be collected. No significant or unquantifiable inputs of fresh or contaminated water to the wetland should exist. Data should be collected for at least one year after system construction and preferably for several years. This ensures that short term effects associated with chemical properties of the compost will not unduly bias results, and that the systems will be evaluated with an established plant cover.

The screening conditions described above exclude from analysis many wetlands that were constructed using different designs and materials (e.g. the TVA wetlands in southern Appalachia) or that do not have exact influent points. We do not intend to imply that these sites are inferior to the ones discussed. Many of these wetlands are very effective (Girts et a]. 1987, Brodie et al. 1988), however, their inclusion in this paper would complicate the interpretation of the results. We leave comparisons of the effectiveness of wetlands constructed with different designs to other papers.

Materials and Methods

The surface area of each study wetland was determined from field measurements or engineering drawings. Water flows were determined using a bucket and stop watch. All flow rates reported are the average of three to five measurements. Raw and acidified water samples were collected for chemical analysis. Samples were not filtered prior to acidification because 1) previous comparisons of filtered (0.45 um) and unfiltered samples showed negligible differences in metal concentrations, and 2) regulatory standards are based on total (unfiltered) metal concentrations. Total iron was determined on the acidified samples by ICP spectroscopy. Sample pH was measured both in the field and in the laboratory. For influent samples discussed in this paper, the results were not substantially different, therefore laboratory values are reported.

Study Sites

Somerset Wetland

The Somerset wetland, located in Somerset County, PA, treats water draining from 12-year-old surface mine spoils. It was built in 1984. Originally, seven seeps existed on the property, but a drainage system was installed that collects all drainage into a single pipe that serves as the influent to the 2 wetland. The system consists of two cells (277 m and 268 M2) connected in series, each constructed with 30 cm of crushed limestone and 45 cm of mushroom compost. A dense growth of cattails covers both cells.

The site was first sampled in March 1987. Monthly sampling of water and flow rates was initiated in November 1988. Water samples were collected from the influent pipe, between cells, and from the effluent pipe. Flow measurements were made at the influent and effluent pipes. Loading calculations are based on the average of the inlet and outlet flow rates.

Latrobe Wetland

The Latrobe wetland, located in Westmoreland County, PA, treats water draining from both reclaimed surface spoils and an abandoned drift mine. The wetland was constructed in June 1987. Water is collected in a shallow pit and flows down a 30 m long ditch into a wetland system that consists of three rectangular cells in series (695 m^2 , 802 m^2, and 1301 m^2) . The wetland substrate consists of 10 cm of crushed limestone covered with 30-45 cm of mushroom compost. Cattails cover about 80% of wetland surface, most of the open area being due to muskrat activity during the summer of 1988.

Beginning in July 1988, water samples were collected from the influent, effluent and between each cell. Flows were measured at the influent and effluent stations beginning in October 1988. Periodic problems with leakage of water through a berm in the third cell prevented use of all the chemical and flow data collected from the final effluent station. We therefore focused our analytical efforts on the first two cells of the wetland. Loading calculations were based on influent flow rates.

In the summer of 1989, extensive modifications were made to the system. The pit, in which the seepage is collected before flowing into the wetland, was filled with spent mushroom compost. Following this modification the water flowing into the wetland had atypical chemistry (circumneutral pH, high concentrations of dissolved organics and hydrogen sulfide). Data from this period will not be presented. Most of the effects of the modification on wetland influent water chemistry appeared to stabilize in August 1989. Data for August, September and October 1989 are presented. Because of the unusual pretreatment of water at this site, these data should be interpreted with caution.

Friendship Hill Wetland

The Friendship Hill wetland was constructed by the Bureau of Mines for research purposes during the summer of 1988. It is located at the Friendship Hill National Historic Site in Fayette County, PA. Inflow water to the wetland system is drawn out of Ice Pond Run, a small first order stream that drains an abandoned drift mine about 1 km upstream of the site.

Six wetland cells were constructed. Details of the design are included in a paper by McIntire and Edenborn (1990) in these proceedings. All cells contain 15 cm of gravel covered with 45 cm of spent mushroom compost. The cells were planted with cattails in October 1988. Growth resulted in approximately 75% coverage by July 1989.

Data are presented for the summer of 1989 (first growing season) for the three wetland cells designated A2, B2 and C2. The surface areas of the cells are 104 m^2, 103 m^2, and 123 m^2, respectively.

While cells at the Somerset and Latrobe wetland are connected serially (cell 1 flows into cell 2), the Friendship Hill cells are parallel. Because all three cells receive water from a common source, they can be considered experimental replications. Flow rates to all cells are controlled by valves which are monitored and adjusted weekly. Water samples are collected from the common influent pool and from the effluent of each cell.

RESULTS AND DISCUSSION

Somerset Wetland

Table 2. Influent water at the Somerset Wetland.

Date	Flow	pH	Inflow Fe		
	L min^{-1}		mg L^{-1}	g day^{-1}	gdm
03-20-87	19	3.2	193	5280	9.7
11-22-88	24	4.0	24	829	1.5
03-22-89	49	3.9	51	3599	6.6
04-11-89	29	3.7	122	5095	9.3
05-18-89	44	3.4	148	9377	17.2
06-16-89	25	3.8	337	12132	22.3
07-11-89	21	3.3	284	8588	15.8
08-16-89	10	3.3	310	4464	8.2
09-14-89	8	5.1	243	2799	5.1
10-24-89	11	5.1	169	2677	4.9
12-14-89	6	4.6	231	2096	3.9

Influent water at the Somerset wetland had an average pH of 4.0 and ranged from 3.2 to 5.1 (Table 2). Iron concentrations and loading varied considerably over the sampling period. Iron concentrations always decreased with flow through the first cell and, except when iron concentrations were less than 10 mg L^{-1} , showed further decreases with flow through the second cell (Figure 2a). Effluent iron concentrations varied considerably, ranging from 3 mg L^{-1} to 159 mg L^{-1} .

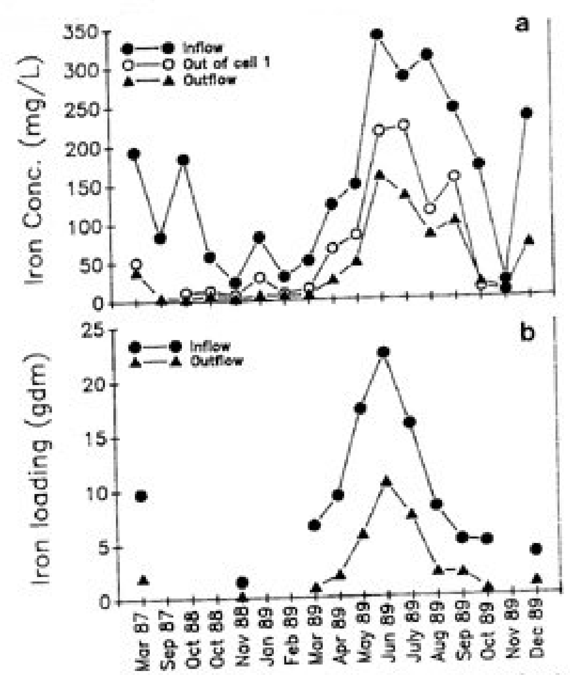

Figure 2. Iron chemistry at the Somerset wetland: a) iron concentrations at the inflow, cell one outflow and cell two outflow sampling stations; b) area-adjusted iron loading at inflow and cell two outflow stations.

Area-adjusted iron removal (the difference between influent loading and effluent loading in Figure 2b) displayed less variability than the area-adjusted loading. The average area-adjusted iron removal was 6.3 gdm (s=3.4). The lowest iron removal rates were associated with very low influent loading (e.g. Nov 1988, Dec 1989), not with any apparent failure of the wetland during periods of high loading. The highest iron removal rates, more than 11 gdm in May and June 1989, occurred when loading rates were also highest. During this period, performance of the wetland from a concentration efficiency standpoint was the lowest observed (53% in June).

Latrobe Wetland

Table 3. Influent water at the Latrobe wetland.

Date	Flow	pH	Inflow Fe		
	L min^{-1}		mg L^{-1}	g day^{-1}	gdm
10-14-88	38	3.1	215	11,765	7.9
11-11-88	38	3.1	226	12,366	8.3
11-28-88	56	3.0	194	15,644	10.5
12-15-88	30	3.3	262	11,318	7.6
01-10-89	53	3.0	210	16,027	10.7
02-01-89	71	2.9	214	21,879	14.6
02-23-89	273	3.1	104	31,056	20.8
03-22-89	330	2.9	79	37,541	25.1
04-19-89	173	3.0	85	21,175	14.1
05-16-89	189	2.9	45	12,247	8.2
05-23-89	114	3.0	49	8,044	5.4
06-7-89	140	3.1	62	12,499	8.4
System modifications					
8-89[1]	37	4.5	119	6,340	4.2
9-89[2]	33	4.6	121	5,750	3.8
10-89[3]	34	4.6	136	6,659	4.5

1 average of two sampling dates
2 average of four sampling dates
3 average of three sampling dates

Before the system modifications, influent water at the Latrobe wetland had an average pH of 3.0. After the modifications, the influent pH averaged 4.6. Iron concentrations ranged from less than 50 mg L^{-1} during high flow periods to more than 200 mg L^{-1} during low flow periods in 1988. Loading rates increased significantly during the winter and spring of 1989 when flows increased by five to ten times, but iron concentrations only decreased by two-thirds.

From a concentration perspective, the wetland had a highly variable effect on water chemistry (Figure 3a). In autumn months of 1987 (not shown), 1988, and 1989, the wet and lowered iron concentrations by 100-150 mg L^{-1}. In spring months of 1988 (not shown) and 1989, iron concentrations were sometimes lowered less than 20 mg L^{-1} .

From an iron-removal perspective, the wetland's performance was less variable. Between October 1988 and April 1989, area-adjusted iron removal only ranged from 2.4 to 6.7 gdm. For an unknown reason, iron removal was very low in May 1989. Removal rates were lower in autumn 1989 than autumn 1988, but this change was a result of decreased loading, not any apparent failure of the constructed wetland.

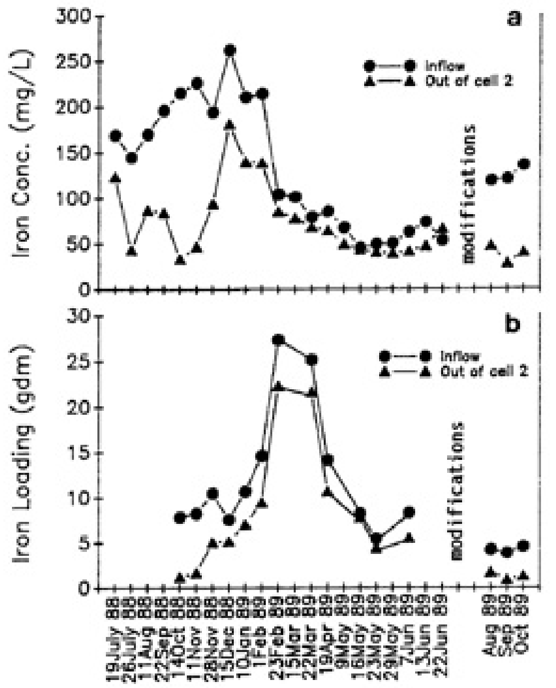

Figure 3. Iron chemistry at the Latrobe wetland: a) iron concentrations at the inflow and cell two outflow sampling stations; b) area-adjusted iron loading at inflow and cell two outflow stations.

Before the modification, the average area-adjusted iron removal rate for the wetland was 3.8 gdm (s=2.0). When the post-modification data are included, the overall average removal is 3.6 gdm (S=1.8).

Friendship Hill Wetland

The influent water at the Friendship Hill wetland had an average pH of 2.7 (Table 4) Iron concentrations varied from 82 to 195 mg L^{-1}. Flow rates were changed three times during the study period and ranged from 1.9 to 7.6 L min^{-1}.

Area-adjusted loadings into the cells varied from 3 to 19 gdm. Slight differences in area-adjusted loading rates for the individual cells were attributable to differences in cell surface areas (compare influent loading lines in Figure 4b, 4d, and 4f).

The wetland cells displayed similar patterns of iron removal (Figure 4). During the spring and summer, all cells displayed consistent iron removal. Average area-adjusted removal rates for this period (May 16 through Sept 19) were 5.0 gdm (s=1.9) for cell A2, 4.1 gdm (s=1.7) for cell B2, and 4.3 gdm (s=1.8) for cell C2. The overall average removal for this period was 4.5 gdm. With 1 gdm calculation based on an average surface area of 110 m^2 per cell, actual values were slightly lower for cell C2, higher for cells A2 and B2.

Table 4. Influent Water at the Friendship Hill Wetland

Date	Flow	pH	Inflow Fe		
	L min^{-1}		mg L^{-1}	g day^{-1}	gdm[1]
05-16-89	7.6	2.8	108	1182	10.8
05-23-89	7.6	2.6	119	1302	11.8
06-06-89	7.6	2.8	182	1992	18.1
06-21-89	7.6	2.7	85	930	8.5
07-06-89	7.6	2.9	82	897	8.2
07-25-89	7.6	2.8	82	897	8.2
08-08-89	3.8	2.8	139	758	6.9
08-23-89	3.8	2.6	144	785	7.1
09-06-89	3.8	2.6	195	1063	9.7
09-19-89	3.8	2.6	176	959	8.7
10-17-89	3.8	2.7	82	447	4.1
11-01-89	3.8	2.7	130	709	6.5
11-14-89	3.8	2.7	133	725	6.6
11-21-89	1.9	2.8	130	354	3.2
11-28-89	1.9	2.8	135	367	3.3
12-05-89	3.8	2.8	176	959	8.7
12-13-89	3.8	2.8	183	997	9.1
12-27-89	3.8	2.7	183	997	9.1
01-03-90	3.8	2.8	111	605	5.5

[1] gdm calculation based on an average surface area of 110 m^2 per cell, actual values were slightly lower for cell C2, higher for cells A2 and B2.

The onset of cooler (autumn) temperatures, iron removal by all cells became more variable. On several days, effluent samples contained more iron than the influent samples. During this period, water levels were lowered by 7-10 cm in all cells. This change may have influenced the iron removal results.

Over the entire observation period, the average removal of cell A2 was 3.5 gdm (s-2.8), of cell B2 was 2.8 gdm (s=3.3), and of C2 was 3.7 gdm (s=2.4). Iron removal for all cells over all dates averaged 3.3 gdm.

Model Evaluation

The relationships between area-adjusted iron loading and iron removal for the three wetlands are shown in Figure 5. For the Somerset and Latrobe wetlands, which consist of cells connected serially, loading and removal rates were calculated for individual cells. This resulted in higher estimates of area-adjusted loading and removal than were obtained for the whole wetland systems (Figures 2b and 3b) because influent loadings were divided by only the area of each particular cell, not the entire wetland.

The Friendship Hill wetlands showed little relationship between iron loading and removal (Figure 5c). However, the maximum loadings, 18-19 gdm, were much less than the maximum loadings at the Somerset and Latrobe sites. Because the proposed model relies upon a broad range of loadings, conclusions about the iron removal capabilities of the Friendship Hill wetlands cannot be made at this time.

The Somerset site exhibited a strong relationship between area-adjusted iron loading and removal (Figure 5a). At iron loadings less than 15 gdm (n=11), a significant linear relationship between the two parameters existed.

Removal = 0.71 X Load - 1.07 (r=.88, P<.05) (6)

As loading increased beyond 15 gdm, no further increase in removal was observed.

Removal = 0.17 X Load + 6.30 (r=.45, P>.05) (7)

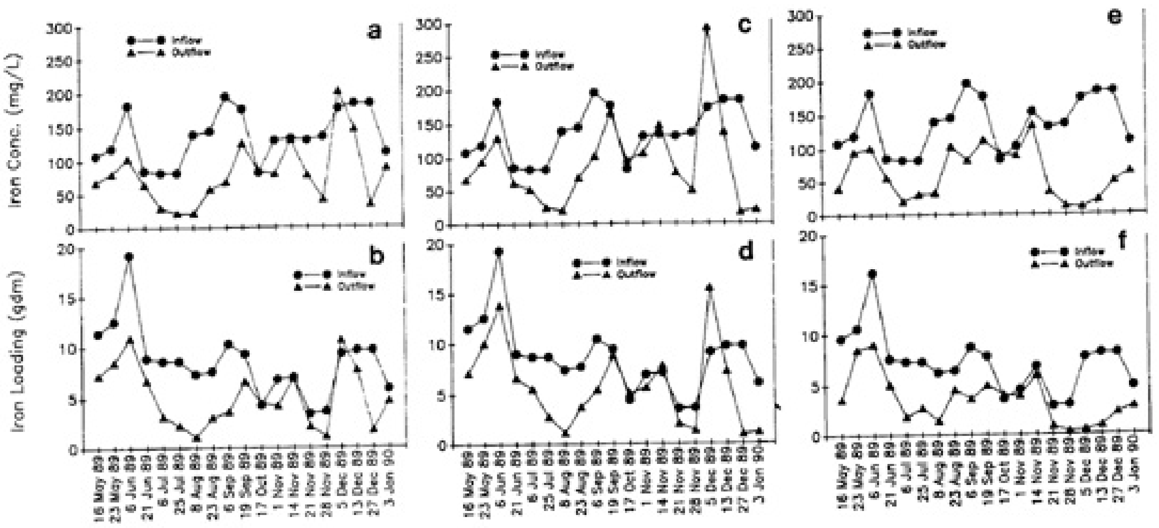

Figure 4. Iron chemistry at the Friendship Hill experimental wetlands. Inflow and outflow concentrations of iron are shown in a, c, and e. Area-adjusted iron loadings at the inflow and outflow stations are shown in b, d, and f.

The average removal of these nine high-loading observations was 10.6 gdm (s.e. = 1.1). This value is an estimate of the iron removal capability of the Somerset wetland.

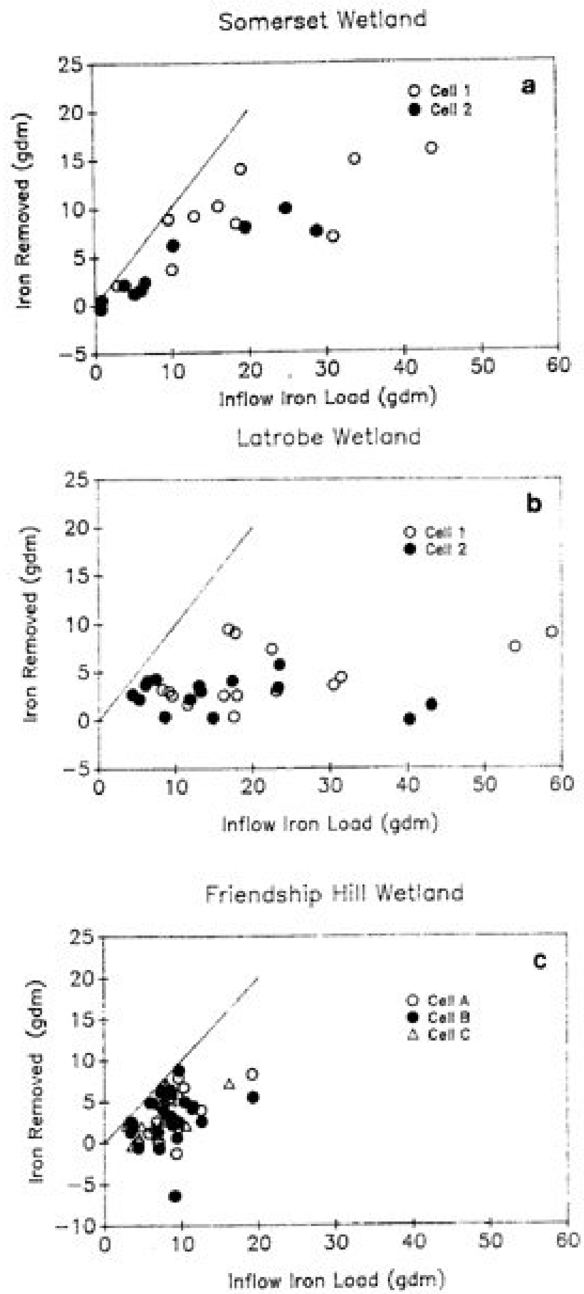

Figure 5. The relationship between area-adjusted iron removal and area-adjusted iron loading at the a) Somerset wetland, b) Latrobe wetland, and c) Friendship Hill wetlands. The straight line represents 100% removal (iron removal = iron loading).

No relationship existed between area-adjusted iron loading and removal at the Latrobe wetland (Figure 5b). This finding was not a result of insufficient variation in iron loading. The range of loadings at the Latrobe site was similar to that at the Somerset site. At loadings greater than 15 gdm, iron removal at the Latrobe site averaged 4.6 gdm, less than half that observed at the Somerset site. Two significant differences in water chemistry at the sites may contribute to these differences in iron removal. The influent pH at the Latrobe wetland averaged a full unit less than that at the Somerset site (3 vs 4). Lower pH may inhibit microbial processes that contribute to iron removal or decrease the stability of precipitated iron oxyhydroxide and sulfide compounds. Close scrutiny of the data results in contradictory evidence with regard to this hypothesis. The highest iron removal rates at the Somerset site were not associated with the highest influent pH values (which ranged as high as 5.1, see Table 2). However, at the Latrobe site the highest iron-removal rates occurred when the wetland was also increasing the pH of water as it flowed through the wetland (Hedin and Hammack, in review).

A second difference between the Somerset and Latrobe sites is the makeup of the high iron loadings. At the Somerset site, high loadings (>15 gdm) were due to high concentrations of iron (122-337 mg L^{-1}) combined with moderate flow rates (10-44 L min^{-1}). At the Latrobe site, high loadings were dye to high flows of drainage (273-330 L min^{-1}) combined with moderate iron concentrations (79-104 mg L^{-1}). It is possible that iron removal rates are correlated with iron concentration. Higher iron removal rates may occur at higher iron concentrations. If this hypothesis is correct, then it may be necessary in future analyses of wetland performance to separate loading estimates into their flow and concentration components.

A common finding at all sites was that complete iron removal (< 1 mg L^{-1}) did not occur, even at very low loadings. Thus, the capability to remove 10 gdm at high loadings does not translate into complete iron removal at loadings less than 10 gdm. At the Somerset site, high loading events resulted in an average removal of 10.6 gdm. At loadings less than 15.0 gdm, iron removal averaged 54% of the inlet load. This decreased iron removal capability cannot be attributed to simply a concentration effect as several low loadings occurred-when iron concentrations were greater than 100 mg L^{-1} .

Implications for Wetland Sizing

If the data presented here represent a crude estimate of iron removal capabilities in constructed wetlands, how does this bode for systems being built today using the original flow-dependent criteria? Sizing calculations for several hypothetical systems are shown in Table 5. Sizing estimates are made based on the original flow criteria and loading criteria developed from the data presented in this paper. We assume with the loading criteria that variation in iron removal results from pH effects, and that wetlands with pH 4 influents can remove 10 gdm of iron, while wetlands with pH 3 influents remove only 4 gdm of iron.

Table 5. Sizing Needs for Hypothetical Wetland Systems

system	pH	Influent Fe mg L^{-1}	Influent flow L min^{-1}	Required Size (m^2) based on: flow[1] (5)	flow[2] (15)	load[3]
A	4	25	30	150	450	108
B	3	25	30	150	450	270
C	4	150	50	250	750	1080
D	3	150	50	250	750	2700

1 5.0 m^2 per L min^{-1} flow (Kleinmann et al. 1986)
2 15.0 m^2 per L min^{-1} flow (Girts et al. 1987)
3 pH 3: 4 gdm (this paper)
pH 4: 10 gdm (this paper)

Comparisons of wetland sizes based on flow and loading criteria indicate that wetland size estimates differ considerably depending on iron loading and pH (Table 5). For the highly contaminated drainage shown in systems C and D, the loading criteria suggest larger wetland needs than are suggested by either flow criterium. At pH 3, the methods differ by more than 300%.

For low flows of moderately contaminated water (systems A and B), the largest wetland sizes are produced by the 15 m^2 flow criterium. This finding probably reflects the fact that the 15 m^2 criterium was developed empirically from the size:flow relationships of wetlands that successfully lowered iron concentrations to regulatory levels. The iron removal criteria developed in this paper were derived from high-loading situations. Because iron removal capabilities appeared to decrease under low-loading situations, it is possible that larger areas of wetland are needed for removal of the last 10-20 mg L^{-1} of iron.

These calculations should be considered preliminary, particularly for the low pH systems. Clearly, more data from these and other systems are necessary to confidently characterize the iron removal capabilities of constructed wetlands. Papers in this session by Kepler (1990) and Stark et al. (1990) should provide additional iron removal information for sites with pH 5 and pH 6, respectively.

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