IRON LOADING, EFFICIENCY AND SIZING IN A CONSTRUCTED WETLAND RECEIVING MINE DRAINAGE [1]

by

Lloyd R. Stark
S. Edward Stevens, Jr.
Harold J. Webster
William R. Wenerick [2]

Abstract. The Simco #4 wetland was constructed near Coshocton, Ohio to treat a deep mine discharge in November 1985. It consists of three wetland cells totaling an area of 2623 m^2. It was planted with rhizomes of Typha latifolia (cattail) and over the course of three growing seasons it has evolved into a cattail-rice cutgrass (Leersia oryzoides) wetland. In 1988, Simco had 80% vegetation cover and a cattail stem density approaching 19 shoots/m2. Wetland substrate depth was 65 cm, and the depth of surface water was 11 cm. The discharge averaged 111 mg L total iron and a flow of 328 L/min. The treatment of water with respect to total iron has generally improved with age, averaging 62% in efficiency (Efficiency = Influent Fe - Effluent Fe/Influent Fe). Higher treatment efficiencies occurred in the summer and fall. Iron loading to the wetland is inversely correlated to treatment efficiency for total iron (r2=47%). Therefore, as the daily mass of iron entering the wetland increased, the ability of the wetland to remove iron from the water decreased. This relationship, however, appeared to be dependent on the age of the wetland. With increasing wetland age, iron loading had less effect on efficiency. An analysis of loadings and outlet iron concentrations revealed a recommended loading of <47 kg Fe/day and a preferred loading of <28 kg Fe/day. Simco has removed an average of 13.6 g Fe/day per m^2 of wetland. However, Simco has effectively treated water having iron loadings of 10 g Fe/day per m^2 of wetland. The implication of this study at Simco was to recommend a maximum iron loading to the system in order to ensure adequate water treatment. The great variation in flow rates at Simco translates into the need to expand the current constructed wetland area in order to handle the high iron loadings of spring.

Additional key words: acid mine drainage, water treatment, Typha latifolia L., flow rates, Leersia oryzoides (L.) Sw.

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[2] Lloyd R. Stark is a Research Associate and William R. Wenerick is a Research Assistant in the

Department of Biology, The Pennsylvania State University, University Park, PA 16802; S. Edward Stevens, Jr. occupies the Chair of Excellence in Molecular Biology, Department of Biology, Memphis State University, Memphis, TN 38152; Harold J. Webster is an Assistant Professor, Department of Biology, DuBois Campus, The Pennsylvania State University, DuBois, PA 15801. Publication in this proceedings does not preclude authors from publishing their manuscripts, whole or in part, in other publication outlets.

Introduction

Constructed wetlands are currently used as an alternative to the chemical treatment of acid mine drainage. In the last decade, well over 100 wetlands have been installed in northern Appalachia at active or abandoned coal mining sites (Kleinmann and Girts 1987). As of June of 1989, there were about 140 constructed wetlands currently in place as treatment systems in Pennsylvania (pers. comm., B. Hellier, PA Department of Environmental Resources, Hawk Run office). The principal water quality problems are high levels of Fe, Mn, Al, and low pH. Federal water quality standards require mine discharges to have a pH of 6 - 9, average total Fe of $\leq$3 mg/L, and average total Mn of $\leq$2 mg/L (U.S. Code of Federal Regulations 1981). Because of the prohibitive cost of using conventional chemical treatment (lime, soda ash, sodium hydroxide, limestone, hydrated lime, or caustic soda), wetlands are now commonly suggested as an inexpensive alternative or supplemental treatment system for coal mine drainage. The popularity of using wetlands for this purpose stems from reports of freshwater wetlands improving the quality of influent mine drainage (Wieder and Lang 1982).

With respect to total iron, treatment efficiency (Inlet [Fe]-Outlet [Fe]/Inlet [Fe]) is often used as an indicator of wetland performance (Kleinmann and Girts 1987). This measure yields a percentage which is useful in determining the performance of the wetland. For example, an efficiency of 70% indicates that the treatment system is lowering Fe concentrations between inlet and outlet by 70%. However, efficiency does not take into account flow rates, and thus taken alone is not very informative (Wieder 1988). When flow rates are included in calculations of wetland performance, it is possible to construct a quantitative budget reflecting the mass of iron (or other parameter) entering and leaving the wetland (e.g., Stillings et al. 1988). Influent iron to the system is termed iron "loading," and can be calculated as kg Fe/day. Loading (L/min x mg/L x 0.00144) is a better means of assessing influent iron levels than iron concentration, especially if inflow rates vary. For example, source water with 25 mg/L Fe at 378 L/min (100 GPM) discharges more than twice the iron to a wetland or stream than source water with 50 mg/L Fe at 75.6 L/min (20 gal/min): 13.6 vs. 5.4 kg Fe/day, respectively.

There have been no comprehensive studies to determine the optimal size of a wetland receiving a particular water flow rate and quality. Initially, flow rate alone was used to estimate wetland size. Kleinmann et al. (1986) suggested 5 m^2 of wetland for each L/min of mine drainage. After surveying constructed wetlands that were one to two years old, Girts et al. (1987) observed that the most efficient systems had a ratio of 15 m^2 per L/min flow. Brodie et al. (1988) suggested an iron loading of 1.92 g Fe/day per m^2 wetland when the influent pH exceeds 5.5 (=0.75 m^2 per mg Fe/min). This figure was based on efficiency studies of several wetlands in Tennessee, and represents the first time that loading, rather than flow, has been used in determining the appropriate wetland size. Although the optimal wetland size may be infinitely large, the area available for wetland construction is usually limited, necessitating calculations on minimum sizing criteria for specific loadings. Ultimately, several chemical parameters of the water in conjunction with flow ranges should be factored into a determination of minimum size. This article explores the seasonal performance of a constructed wetland with respect to iron over a period of four years, presents an inverse relationship between iron loading and treatment efficiency, and discusses the sizing parameters for the wetland under study.

Materials and Methods

The Simco #4 Wetland

In November 1985, construction of the Simco #4 wetland in Coshocton Co., Ohio was completed. It consisted of three wetland cells in sequence separated by small settling pools. The substrate consisted of a layer of crushed limestone (15 cm) covered with a layer of spent mushroom compost (45 cm). The total area of the system was 2,623 m^2 (28,233 ft^2; Cell 1 = 850 m^2, Cell 2 = 771 m^2, Cell 3 = 1,002 m^2). The average substrate depth in 1988-89 was 65 cm, while the average depth of standing water above the substrate was 11 cm. Typha latifolia (cattail) rhizomes were transplanted to an initial density of 3-4/m2. Over three growing seasons, Simco has evolved into a cattail-rice cutgrass (Leersia oryzoides) wetland with nearly 80% cover and a cattail stem density approaching 19 shoots/m^2. Other details regarding construction and biological monitoring can be found in Stark et al. (1988).

In August 1987, the flow configuration was changed so that Cells 1 and 2 received one-half of the mine discharge, and a series of straw dikes was installed (Figure 1). The chief concern at the site has been to reduce the amount and necessity of chemical treatment used to control iron concentrations. Total iron at the seep has averaged 111 mg/L, and flow has averaged 328 L/min (87 gal/min). Influent pH is within compliance, averaging 6.5, and total manganese is near 2 mg/L. Other relevant water data for the inlet and outlet are given in Table 1.

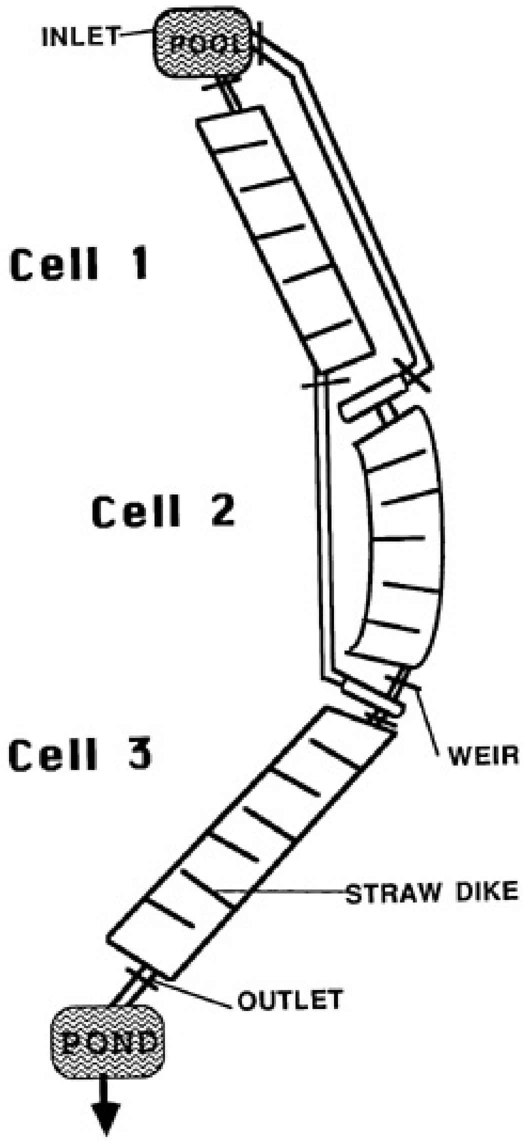

Figure 1. Diagram of the Simco constructed wetland.

Water Sampling and Analysis

Water was collected at the inlet, outlet, and individual cell outlets at two or three week intervals. Water was analyzed by the Peabody Coal Lab (through 1987) and the American Electric Power Central Coal Lab (1988 on) for total iron. In the field, pH and flow rates were taken. Total iron was measured using a Perkin/Elmer 4000 and 5000 atomic absorption spectrophotometer using standard techniques. Water data were stored and manipulated on the IBM 370/3081 mainframe computer using the Statistical Analysis System (SAS Institute Inc. 1982).

Table 1. Mean (± one standard deviation) water quality at Simco #4 inlet and outlet, November 1985 through October 3, 1989.

	Outflow* (L/min)	pH (S.U.)	Tot. Fe (mg/L)	Tot. Mn (mg/L)	Acidity (mg/L)	Alkalinity (mg/L)	Sulfate (mg/L)	T.S.S. (mg/L)	Temp. (°C)
Inlet	----	6.5± 0.2	111± 26	2.0 ± 0.6	123± 82	87± 33	1146± 225	40 ± 24	12.8±1.6
Outlet	328±186	6.4± 0.3	42± 23	2.1 ± 0.6	32± 25	26± 18	1067± 230	50± 27	----
Efficiency	----	−2%	−62%	+5%	−74%	−70%	−7%	+25%	----
(N)	(105)	(74)	(86)	(86)	(86)	(86)	(70)	(73)	(43)

*Inflow rates were first sampled in September 1988 and have been very close to outflow rates through October 1989.

Results and Discussion

Concentration

The inlet water station is the deep mine portal, while the outlet water station is the effluent from Cell 3 (Figure 1). Total iron concentration at the inlet has fluctuated around 100 mg/L, ranging from 73 to 160 mg/L. Outlet concentrations have ranged from over 100 mg/L shortly after construction to 7 mg/L during the summer of 1988 (Figure 2A).

Efficiency

Efficiency of the Simco #4 wetland in removing total iron has averaged 62 percent from wetland installation through October 3, 1989 (about four years; Table 1). Efficiency, computed as follows:

$$\frac{\text{Inlet Fe concentration - Outlet Fe concentration}}{\text{Inlet Fe concentration}}$$

has ranged from a low of 11% in December 1985, shortly after construction, to a high during July through September 1988 of 94%. Generally, the system has improved in efficiency with age (Figure 2B), with the greatest improvement in the first two years after construction.

A seasonal component to efficiency is illustrated by averaging efficiencies for each of the four seasons (Table 2). Higher efficiencies occurred in the summer and fall, whereas lower efficiencies usually occurred during the winter and spring. In the summer of 1988, the average system efficiency exceeded 90% for the first time. However, during the following winter, efficiency reached only 62%, 10% lower than the efficiency of the previous winter. This marked the first decrease in average seasonal efficiency (i.e., for a given season) since wetland installation. Previous to this, winter efficiency had improved with each successive winter (Table 2). This finding prompted an investigation into the patterns of iron loading for the wetland, and the relationship between loading and efficiency.

Loading

Loading is defined as an estimate of the daily mass of iron entering the wetland system:

$$\text{kg Fe/day (loading)} = \text{Inlet Fe concentration (mg/L)} \times \text{Inflow (L/min)} \times 0.00144$$

The calculated loading rate is an estimate because water samples and flow rates were sampled every second or third week. The highest loads to the system occurred in winter and spring, whereas relatively low loadings occurred during summer and fall. Iron loading closely corresponded to flow rates, especially from mid-1987 on (Figure 3). While the concentration of iron in the seep water has remained relatively stable, flow rate has ranged from 114 to 1,116 L/min, and closely mirrored loading. Higher flows have occurred each spring, with the greatest flows recorded since installation during spring of 1989, when rainfall totals were above normal. Lower flows have coincided with the summer and fall months, with the unusually dry summer/fall of 1988 resulting in the lowest flows since wetland installation. Generally, as flow rate declined, the concentration of iron at the seep increased; as flow increased, iron concentration declined (Figure 4). This rough inverse relationship between inlet total iron and flow results in higher iron concentrations at the seep during summer and fall, and lower concentrations during winter and spring. Despite this relationship, the high variation in flow rates results in a close correspondence between iron loading and flow. Therefore, iron loading is determined more so by flow rates than by iron concentration.

Table 2. Seasonal efficiencies (%: Inlet Fe – Outlet Fe/Inlet Fe) for total iron at Simco #4.

	1985	1986	1987	1988	1989
Spring	—	37	55	63	61
Summer	—	56	62	91	73
Fall	—	53	73	82	64
Winter	28	51	72	62	—

Spring: March – May
Summer: June – August
Fall: September – November
Winter: December – February

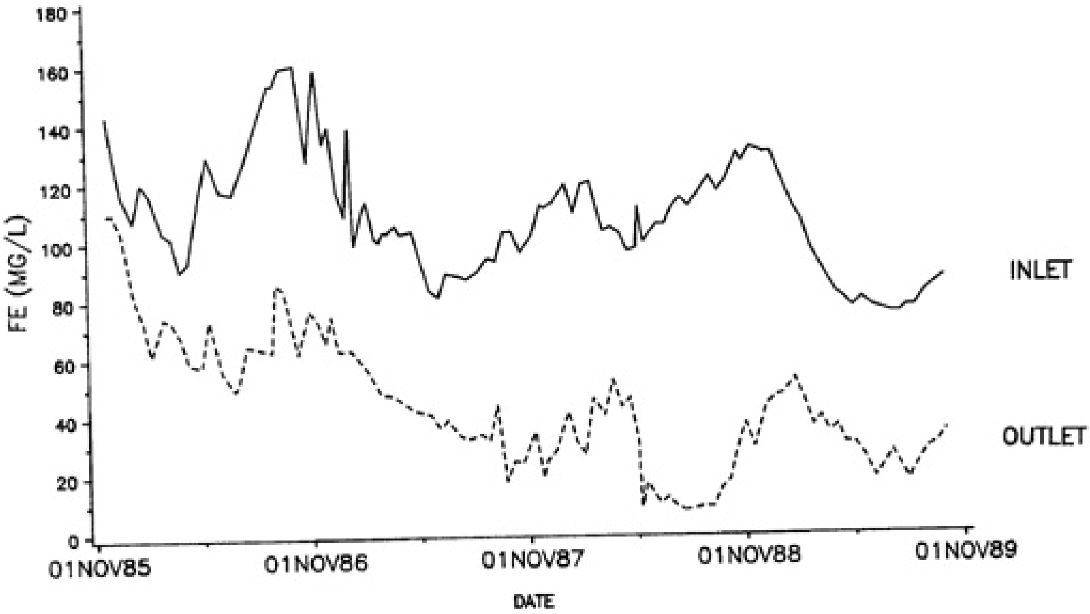

Figure 2A. Inlet and outlet concentrations of total iron at the Simco wetland.

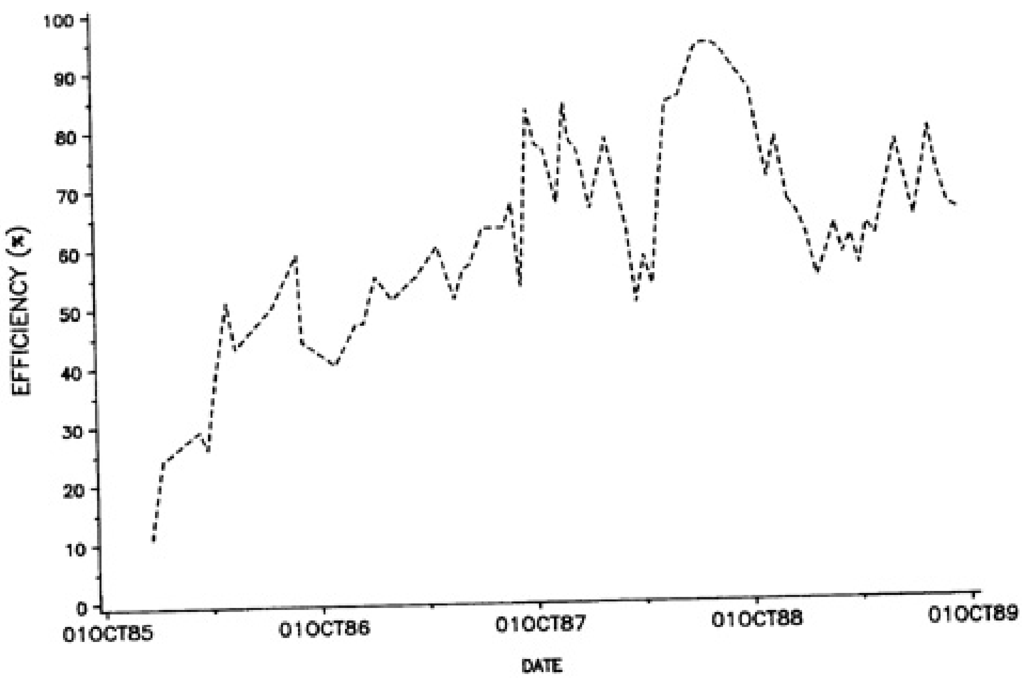

Figure 2B. Treatment efficiency (%) for total iron at the Simco wetland (Efficiency = Influent Fe - Effluent Fe/Influent Fe).

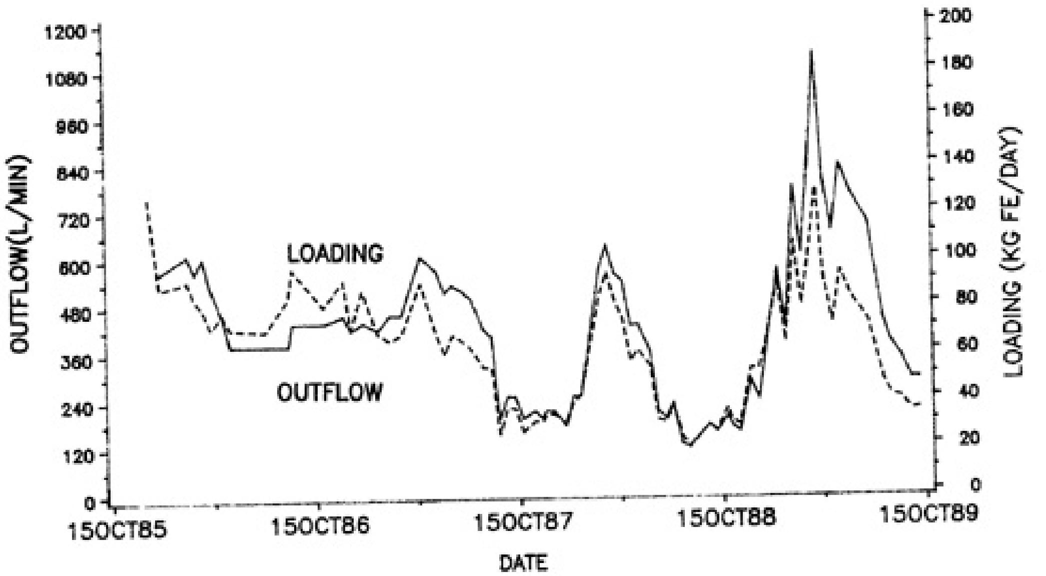

Figure 3. Iron loading in relation to outflow at the Simco wetland.

Noting that (1) the very low flows of the summer of 1988 coincided with the highest treatment efficiencies recorded at Simco, and (2) that efficiencies dropped off somewhat when normal flows resumed, an analysis of the relationship between iron loading and treatment efficiency was undertaken. A plot of efficiency versus iron loading by year (Figure 5) is revealing. This scatterplot represents water data from December 19, 1985 (when flow data and water data were first available) through October 3, 1989.

A regression of efficiency vs. loading yields the following linear equation:

$$\text{(a) Efficiency} = (-0.46)\ (\text{Loading}) + 90$$

$$r2 = 47\%\ (p<0.01)$$

As loading to the wetland system increased, the efficiency decreased with respect to total iron. Conversely, the higher efficiencies corresponded with the lower loadings. Because a major component of loading is flow, the inverse relationship between flow and efficiency is expected (Figure 6). While other factors certainly affect efficiency, the relationship between loading and efficiency was apparent from 1985 to 1988. However, in 1989 this relationship between iron loading and wetland treatment efficiency weakened noticeably. In 1989, flows increased markedly following heavy spring rains; however, system efficiency remained high and did not reflect the increases in iron loading. During February to July 1989, flows averaged 782 L/min, and the average loading was 91 kg Fe/day. The resulting average efficiency of 0% over this period was more than twice the predicted efficiency of 27% going into this period. This may indicate a wetland aging effect where the wetland processes are improving as the system becomes fully established. Hence, the Simco wetland treated higher iron loadings more efficiently in its fourth spring than in earlier springs. Previous to 1989, low loadings always occurred in the warmer months and yielded high efficiencies. However, late in 1989 (December) loadings dropped below 30 kg Fe/day, and yet efficiencies remained below 70%. We attribute these depressed efficiencies to a cold weather effect.

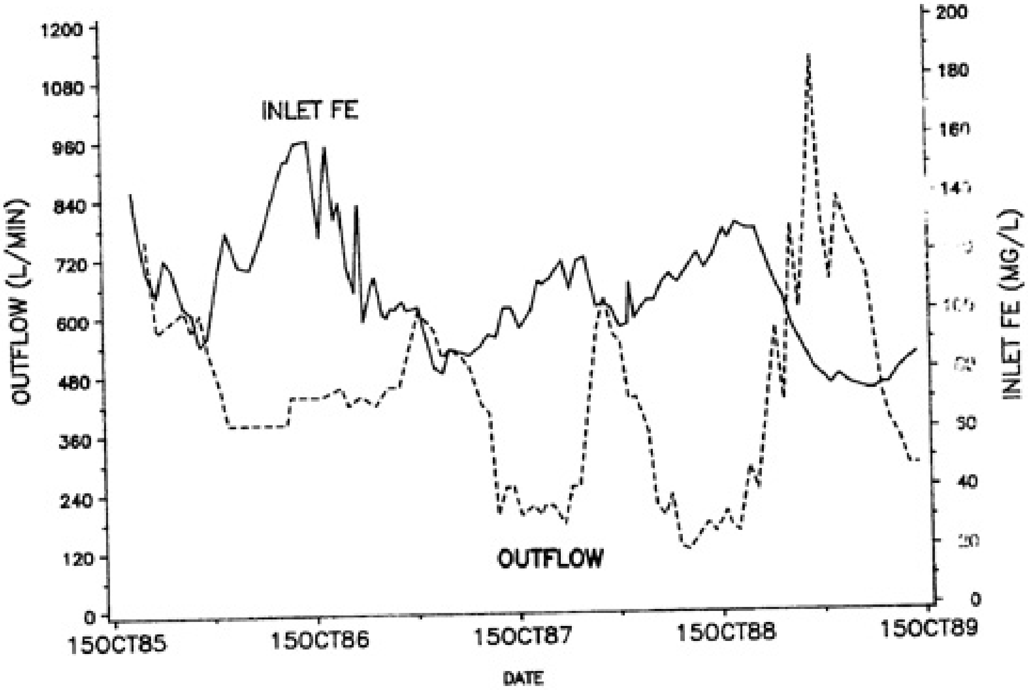

Figure 4. The relationship between outflow and total iron concentration at the inlet at the Simco wetland.

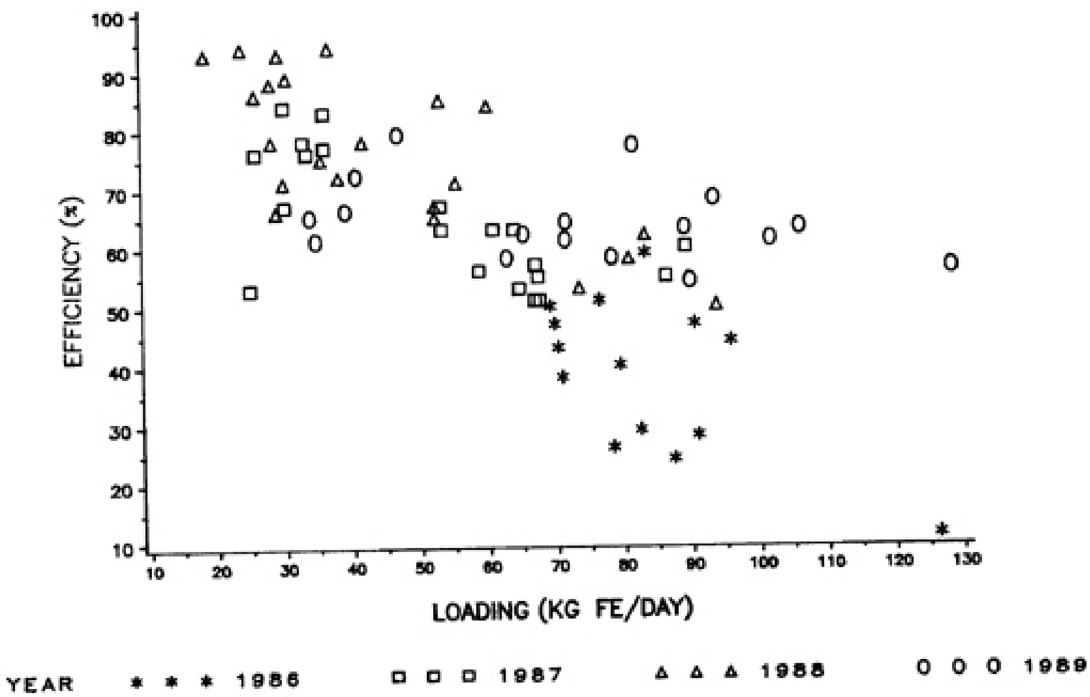

Figure 5. Plot of treatment efficiency for total iron versus iron loading at the Simco wetland (by year).

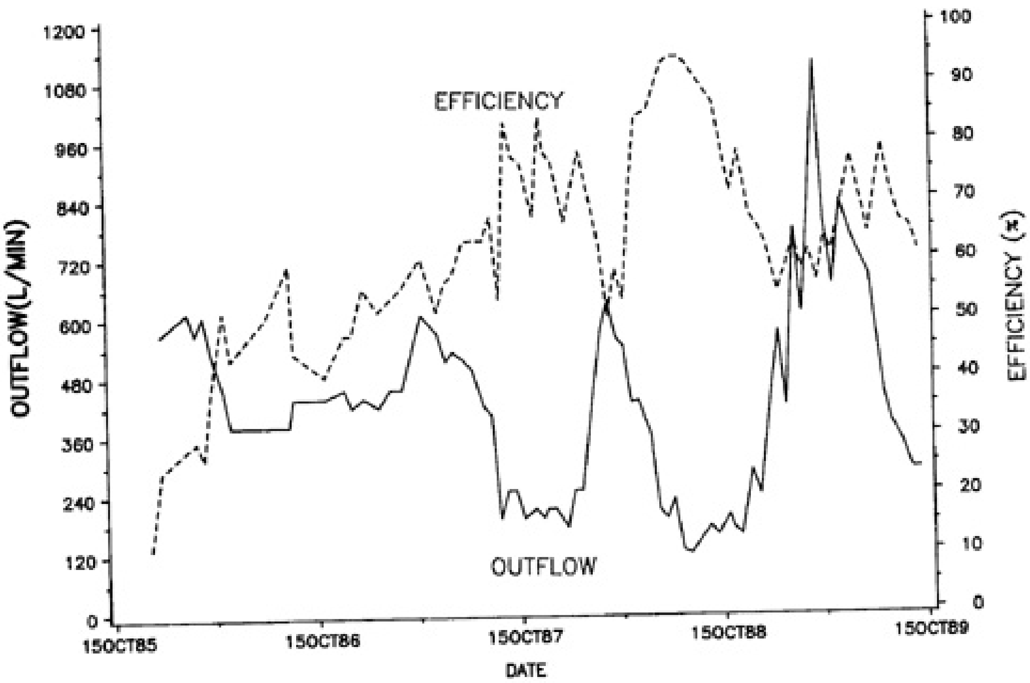

Figure 6. The relationship between treatment efficiency for total iron and outflow at the Simco wetland.

Wetland Sizing

One approach to the question of sizing is to (1) isolate those periods during which the wetland was treating the water effectively; (2) determine the loading to the wetland at these times; (3) assume that these loadings represent the preferred loading maxima for the system; and (4) derive a coefficient of size based on the loading at these times and the size of the wetland in question. Working backwards like this is necessary because at the time of wetland construction, no data on sizing existed. Because of the presence of settling ponds downstream of the Simco #4 wetland and within the permitted area, total Fe at the wetland outlet does not have to be <3.0 mg/L to meet compliance. Rather, if total Fe is lowered by the wetland to approximately 25 mg/L at the outlet, on-site chemical treatment can be avoided. When outlet iron concentrations were <25 mg/L, the iron loading at Simco averaged 47 kg Fe/day (Table 3). When outlet iron concentrations exceeded 25 mg/L, loadings averaged about 57 kg Fe/day. Correspondingly, when loadings were <47 kg Fe/day, the mean outlet iron concentration was 25.1 ± 11. 0 mg/L (X ± S.D.). Therefore, the recommended iron loading at Simco should be under 47 kg Fe/day. In order to ensure that chemical treatment is not required, preferred loadings would be in the neighborhood of 28 kg Fe/day; this would eliminate much of the variation in outlet iron concentration.

In order to make comparisons among several wetlands with respect to the question of sizing, iron loading and removal can be based upon a unit wetland area, a square meter. Therefore, the grams of iron loaded or removed to a wetland per day per square meter can be termed gdm load and gdm removed. This convention is used for the other similar papers in this session. A recommended loading not to exceed 47 kg Fe/day and preferred loading of <28 kg Fe/day correspond to 17.9 and 10.6 gdm, respectively.

The gdm load and gdm removed are positively correlated (r2=46%; P<0.01); as loading to the wetland increased, removal rates per m^2 also increased. With respect to efficiency, as loading increased while efficiency decreased, the mass of iron removed actually increased. This finding underscores the reason why iron removal averages (about 13 gdm for Simco) cannot be used in computations of wetland sizing: while Simco has removed a high of 27 gdm (April 4, 1989) it did so when the loading was 49 gdm, and thus treatment was not effective on this date. A plot of gdm load and gdm removed over time indicates how the mass of iron removed at Simco corresponds to the mass of iron loaded to the wetland (Figure 7).

Discussion

At the Simco wetland, we can address wetland sizing using past performance and water quality data. For the site in question, iron loading should not exceed 47 kg Fe/day, and preferably be <28kg Fe/day. This translates to a preferred iron loading of 10.6 gdm, or roughly five times the estimate of Brodie et al. (1988) for sites having an influent pH greater then 5.5: 1.92 gdm. Note, however, that compliance levels for iron are not required at the Simco outlet; the iron concentration must be <25 mg/L at the outlet in order to avoid chemical treatment. if compliance levels for iron were required at the outlet, the gdm estimate of Brodie et al. (1988) would likely apply. Our estimate is specifically for Simco, and should be cautiously considered in connection with other sites. The water at Simco is mitigated by the age of the wetland, relatively high pH, low levels of Mn, and presence of alkalinity. Should the pH be lower and influent Mn be greater, then the figure of 10 gdm is probably too high.

Table 3. Mean iron loadings at Simco at a range of wetland outlet iron concentrations (Sept. 1, 1987 through Dec. 31, 1989; gdm = g Fe per day per m^2 wetland).

Outlet Fe (mg/L)	Loading (kg Fe/day)	Equivalent gdm	Loading Range	N
0–15	28.0	10.6	19–37	6
16–25	47.0	17.9	26–94	12
26–35	56.8	21.6	24–128	17
36+	57.5	21.8	25–90	15

Note: When iron loading is <47 kg Fe per day (equivalent to 17.9 gdm), outlet iron averages 25.1 ±11.0 mg/L, N=30.

The efficiency of the Simco wetland is directly related to the iron loading; 47% of the observed variation in efficiency can be explained by the iron loading rate. The implication of this relationship for Simco was that a maximum recommended flow could be established that corresponded to an acceptable level of metal removal. In addition, it points up a possible explanation for the observed seasonal patterns of treatment efficiency in constructed wetlands. Lower treatment efficiencies at Simco occurred in the winter and spring; higher treatment efficiencies occurred during summer and fall. The highest loadings occurred during the highest flows (winter and spring), whereas the lowest loadings occurred during the lowest flows (summer and fall). Therefore, the depressed efficiencies of winter and spring may simply be a result of higher loadings, as opposed to temperature-dependent biological reactions. Seasonally depressed efficiencies at Simco probably result from a combination of factors, one of which is higher iron loadings.

How long wetland treatment systems will continue to remove iron is of concern to all involved with wetlands. A quantitative estimate for Sphagnum-based wetlands is provided by Wieder (1988). However, cattail-compost systems may be fundamentally different and require further study. Perhaps the greatest concern is over precipitated iron accumulating in the sediments over many years, leading to the eventual filling and probable short-circuiting of flow patterns, negating much of the water treatment.

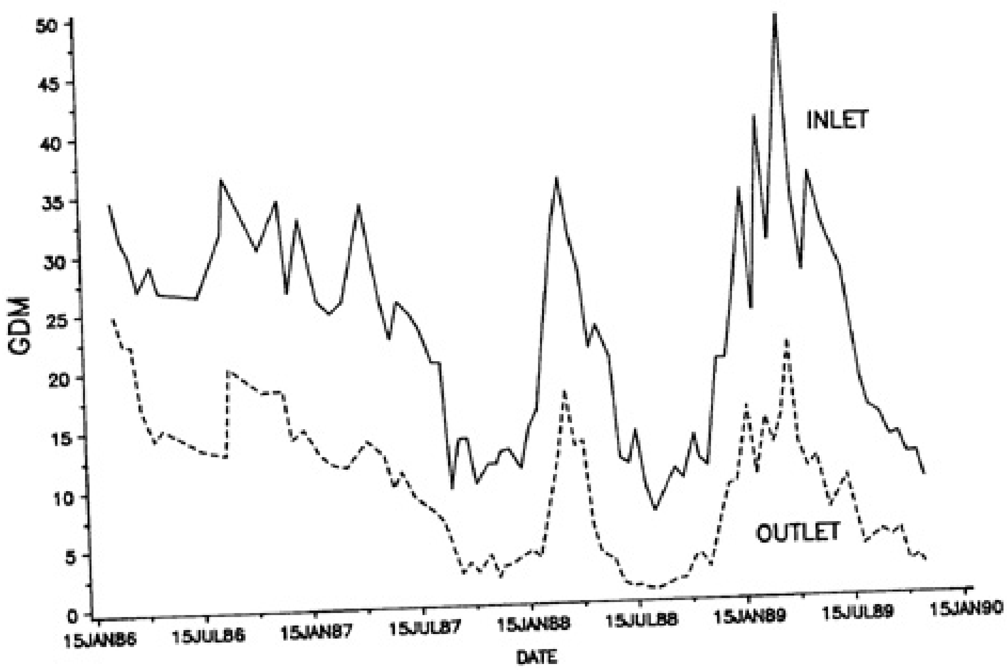

Figure 7. Iron loading and removal on the basis of grams per day per square meter of wetland (gdm load vs. gdm removed).

Future efforts at Simco will focus on projecting rates of sediment buildup with respect to loading and removal.

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