IRON RETENTION AND VEGETATIVE COVER AT THE SIMCO CONSTRUCTED WETLAND: AN APPRAISAL THROUGH YEAR EIGHT OF OPERATION[1]

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Abstract: The Simco constructed wetland near Coshocton, OH, has received mine water containing an average of 89 mg/L at a loading of approximately 15 g Fe/m^2/d since 1985. Its capacity to remove iron is evaluated by analyses of (1) inlet and outlet water chemistry, (2) concentration treatment efficiency over time, and (3) area-adjusted iron retention over time. Since 1990, the wetland system outlet has not required any chemical treatment, meeting Federal compliance levels for iron and pH. Source water iron concentrations have exhibited a gradual tendency to decline over the years. Treatment efficiency has improved over time, exceeding 90% as the wetland aged. Area-adjusted iron retention (g/m^2/d) is a strong positive correlate to iron load ($r= +0.89$), thus devaluing it as an indicator of wetland performance. Treatment efficiency is preferred as a measure of wetland performance for iron retention, because it is significantly negatively correlated to flow rate ($r= -0.46$), iron load ($r= -0.74$), and inlet iron concentrations ($r= -0.44$). The density of cattail (Typha latifolia) shoots has generally increased through the years to a current density of 17 shoots/m^2. Plant diversity and non-cattail species cover, however, have declined since wetland inception. We postulate that the improvement observed with time in the ability of the Simco wetland to retain iron is a result of a combination of factors, namely the presence of moderate mine water quality (near neutral pH, [Fe] <100 mg/L), sound wetland design and subsequent modifications, periodic site maintenance, and high vegetative cover.

Additional Key Words: acid mine drainage, constructed wetlands, iron, water treatment, Typha latifolia

Introduction

Constructed wetlands have been designed and implemented for the treatment of a variety of water pollutants over the last 10 yr. With respect to coal mine drainage, few of these wetlands have been monitored regularly since inception, and therefore data are scant regarding such important questions as longevity and vegetation patterns. In coal mine drainage, the water quality parameters of concern are pH and several metals. Of the metals, iron, manganese, and aluminum may exceed required or recommended outlet concentrations. Surveys indicate that while pH and Mn meet with varying degrees of success in wetland treatment systems, wetlands are usually capable of lowering iron concentrations significantly (Wieder 1989, Hellier 1989). Such wetland treatment is likely dependent on a few critical design parameters, namely the size of the wetland as compared to flow rate and influent metal concentrations, the net acidity of the influent water, and the metal load to the wetland system (Hedin and Nairn 1992).

In this paper, we report on patterns of iron retention and vegetation from a constructed wetland that has been in operation and continuously monitored since 1985. The Simco wetland was installed primarily to treat a seep that contained high levels of total iron and was initially planted with Typha latifolia.

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Methods

Design

In November 1985, construction of the Simco wetland in Coshocton County, OH, was completed. It consisted of three wetland cells in sequence separated by small ponds. 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 3,196 m^2 (including small ponds between cells and connecting ditches). Bed slope was 1%. Typha latifolia (common, broad-leaved cattail) rhizomes were transplanted from a donor site to an initial density of 3 to 4/m^2. In 1989, a fourth wetland cell was added, bringing the system area to 4,138 m^2 (fig. 1).

Water Sampling

Every 2 or 3 weeks, water samples were taken from the system inlet and outlet, as well as from individual wetland cell outlets and the site permit outlet (NPDES point). pH (electrometric), flow rates (flume), and temperature (electrometric) were taken in the field. Water samples were transported on ice to the laboratory, where standard methods (APHA 1985) were used to analyze total and dissolved Fe, total Mn, acidity, alkalinity, conductivity, sulfates, and total suspended solids.

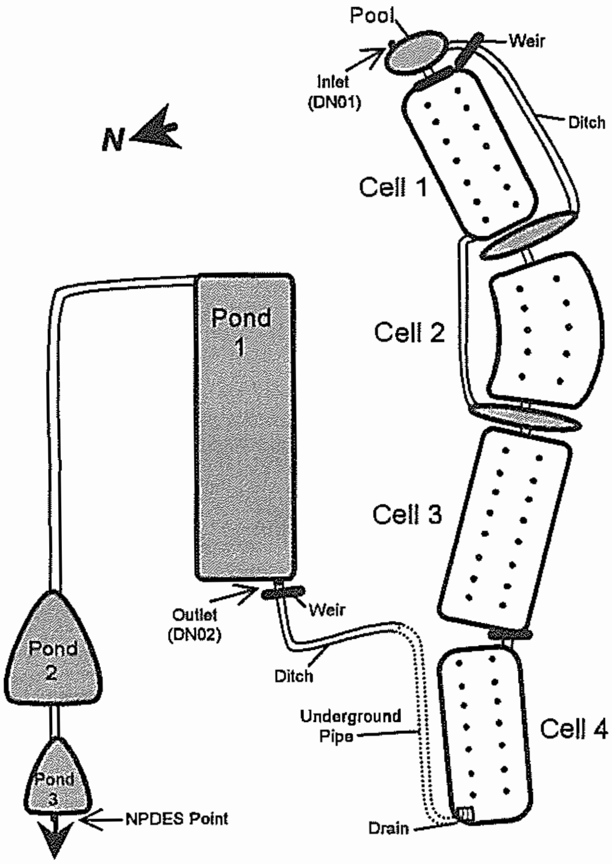

Figure 1. Diagram of the Simco wetland. Points within the cells represent the vegetation sampling stations.

Performance Indices

Two measures are commonly used in the assessment of wetlands treating metals: Treatment efficiency and Area-adjusted Fe retention. Treatment (or concentration) efficiency estimates the percentage of iron retained in a particular wetland:

Treatment Efficiency (%) = $(100)([Fe]_{INLET} - [Fe]_{OUTLET}) \div [Fe]_{INLET}$

Area-adjusted Fe retention (also AART, or mass retention) estimates the mass of Fe retained in the wetland per unit area:

Area-Adjusted Fe Retention ($g/m^2/d$) = $Q\,([Fe]_{INLET} - [Fe]_{OUTLET})\,(1.44) \div A$, where Q is flow rate, A is wetland area, and 1.44 is used to convert minutes to days and milligrams to grams.

At the Simco wetland, the wetland inlet and outlets are well marked; treatment efficiency is based on the iron concentrations found at stations DN01 and DN02 (fig. 1). Since the total area of the system changed in 1989, prior to October 1989, an area of 3,196 m^2 was used in the calculation of area-adjusted Fe retention. After October 1989, 4,138 m^2 was used in this calculation. Only dates where all three parameters were measured (i.e., inlet Fe, outlet Fe, and flow rate) were used in the area-adjusted Fe retention calculations.

Vegetation Sampling

Forty permanent, equidistant sampling stations were established along two parallel transects running the length of the original three-celled wetland system (fig. 1). Each summer (July or August), the percentage cover of vascular and non-vascular plants was assessed using a 0.5 m^2 quadrat. Visual estimates (to the nearest 10%) of cover were determined based on the canopy coverage method of Daubenmire (1970). Owing to the tall and slender nature of cattails, coverage was difficult to assess. As a result, beginning in 1987 stem counts of living cattails were taken in each quadrat, and density was calculated per unit area of wetland accordingly. Species diversity was estimated as the number of species occurring in the 40 sampling stations.

Results

Inlet and Outlet Water Chemistry

The principal pollutant entering the wetland is iron (table 1). Until early 1989, total manganese entering the wetland was above Federal (30-day average) standards (2.0 mg/L). However, since that time inlet Mn has been in compliance. Most other mine water parameters are decreased in concentration as a result of passage through the wetland (table 1).

Inlet and Outlet Iron Concentration. Although seasonal fluctuations occur, in general the inlet [Fe] has declined over the last ten yr (fig. 2) from about 200 mg/L to the current level near 75 mg/L. Upon wetland installation, water quality began to improve at the system outlet. Nevertheless, chemical treatment (sodium hydroxide) was required in addition to wetland treatment during the following periods.

Table 1. Mean (± 1 standard deviation) values for inlet and outlet water parameters at the Simco wetland, 1985-93.

Parameter	Inlet	Outlet	N
pH	6.56±0.16	6.58±0.75	190
Total iron (mg/L)	89.37±25.56	22.63±20.09	190
Total manganese (mg/L)	1.72±0.39	1.96±0.65	191
Acidity (mg/L)	133.80±61.81	28.04±22.94	191
Alkalinity (mg/L)	87.64±26.82	44.02±26.93	191
Conductivity (μomhos/cm)	1,790.10±360.71	1,701.97±336.17	189
Total suspended solids (mg/L)	37.60±16.87	29.71±22.05	190
Sulfate (mg/L)	984.07±233.79	912.63±219.27	174
Temperature (°C)	12.85±1.26	12.00±7.38	128
Flow Rate[1] (L/min)	451.29±272.70	427.50±270.90	95

[1] Paired data from 1987-93; previous to this only outflow data are available.

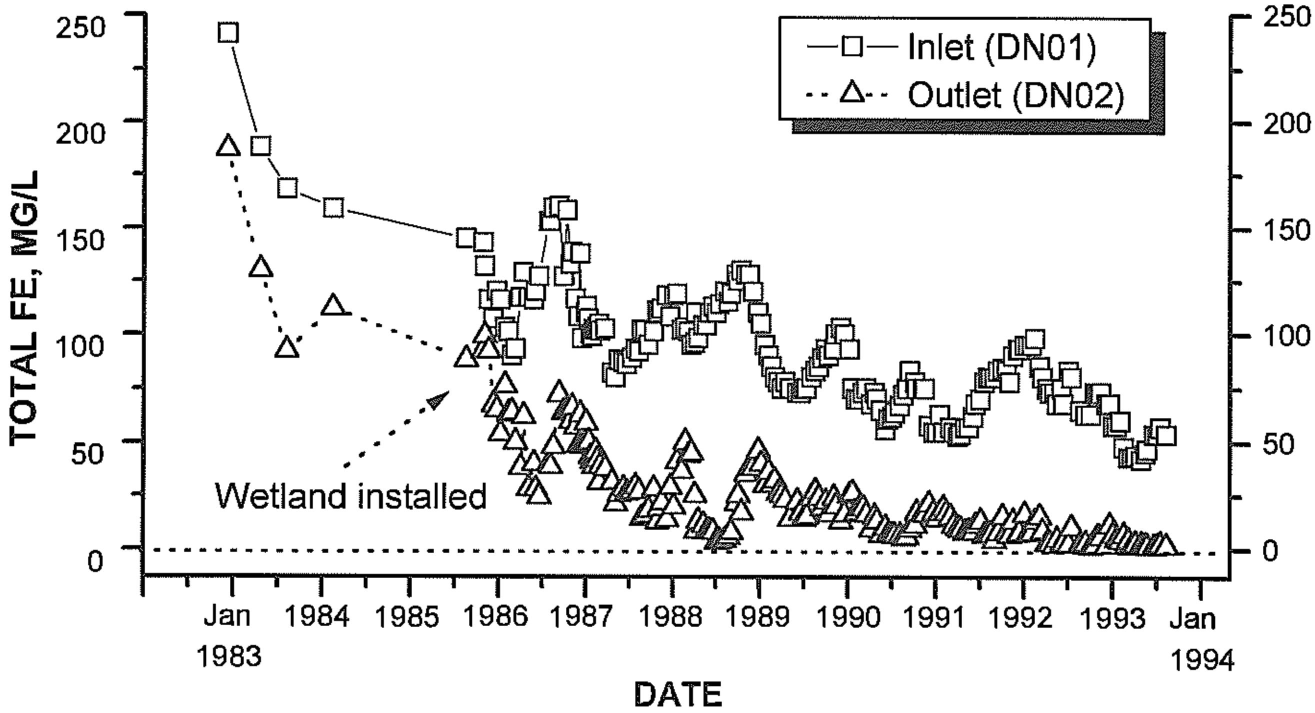

Figure 2. Inlet and outlet iron concentration over time at the Simco wetland. Pre-wetland values are shown from 1983 to 1985.

Chemical treatment and Duration

ON	Pre-wetland, 1980-85	5 yr.
ON	Nov. 1985 - May 1987	19 mos.
OFF	June 1987 - Jan. 1988	7 mos.
ON	Feb. 1988 - Apr. 1988	3 mos.
OFF	May 1988 - Nov. 1988	7 mos.
ON	Dec. 1988 - May 1989	6 mos.
OFF	June 1989 - Jan. 1990	8 mos.
ON	Feb. 1990 - Mar. 1990	5 d.
OFF	Apr. 1990 - Jan. 1994	3+ yr.

During the last 3½ yr, no chemical treatment has been required of water discharging from the wetland. As of August 1993, the chemical treatment facility was removed, as supervised by the Ohio Department of Natural Resources.

Treatment Efficiency, Total Iron. The percentage of iron retained by the Simco wetland has increased over time (fig. 3). Generally, efficiency has been higher during the warmer months and lowest during the winter months. With one exception (the winter of 1991-92), the treatment efficiency has improved each succeeding winter.

Area-Adjusted Iron Retention. This measure has fluctuated widely since the wetland was installed, with a mean value at 10.54 g Fe/m^2/d (±5.57, N=167). The area-adjusted iron load to the wetland has averaged 15.14 g Fe/m^2/d (±10.16, N=167). Plotted against flow rate, area-adjusted retention mirrors the flow rate entering the Simco wetland: as flow rate increases, retention per unit area also increases (fig. 4).

Correlates of Performance Measures. A correlation analysis of the two measures of wetland performance and several iron and flow variables indicates that treatment efficiency and area-adjusted Fe retention are not closely related to one another. These two measures of wetland performance are correlated in opposite directions to iron concentrations, flow, load, and one another (table 2). High treatment efficiencies are attained when low iron concentrations and low flow rates occur (resulting in low iron loads). However, high area-adjusted iron retention occurs in the presence of high iron concentrations and high flow rates (resulting in high iron loads).

Vegetation Patterns

Cattail Stem Density. From the initial planting density of approximately 3.5 stems/m^2 (not measured), cattail density has generally increased with each summer in the upper three cells over the first 5 yr (fig. 5). Over the past three summers, density has been fairly stable near 17 living stems/m^2. In 1993, the mean biomass per cattail plant was 120 g (dry weight), partitioned between above-ground shoots (70 g) and below-ground rhizomes and roots (50 g; n=6). This equates to an approximate dry weight biomass of cattails of 2.04 kg/m^2, of which 850 g is below-ground.

Non-Cattail Coverage. With the exception of 1991, mean total coverage of non-Typha wetland plants has declined since 1987 (table 3). Coverage increased during the first two full summers, to a high of 40% (i.e., approximately 40% of the wetland surface was occupied by non-Typha species). However, currently this coverage has fallen to only 4%.

Shortly after the wetland was installed, a surge of growth by Leersia oryzoides (rice cut-grass) occurred, with this species accounting for a mean cover of 22% in 1987 (table 3). However, Leersia populations have since declined from co-dominant status in 1987 to incidental status by 1992. Only four genera are currently somewhat common in the Simco wetland besides Typha latifolia: Lemna (duckweed), Leersia, and two algal genera, Microspora (a filamentous green) and Oscillatoria (a filamentous blue-green).

Species Diversity. Diversity was highest during the first 2 yr of establishment (12 to 13 species) and has gradually declined from 1987 on, mirroring the decline in non-Typha coverage (table 3). During the last 3 yr, the number of species occurring in the Simco wetland has stabilized near five.

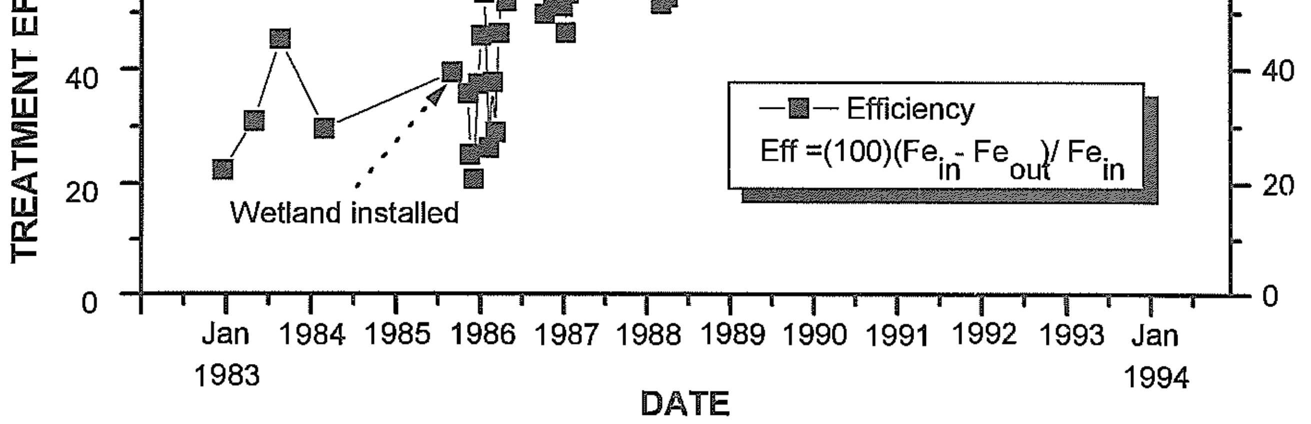

Figure 3. Treatment efficiency for iron at the Simco wetland over the life of the wetland. Pre-wetland values are shown from 1983 to 1985.

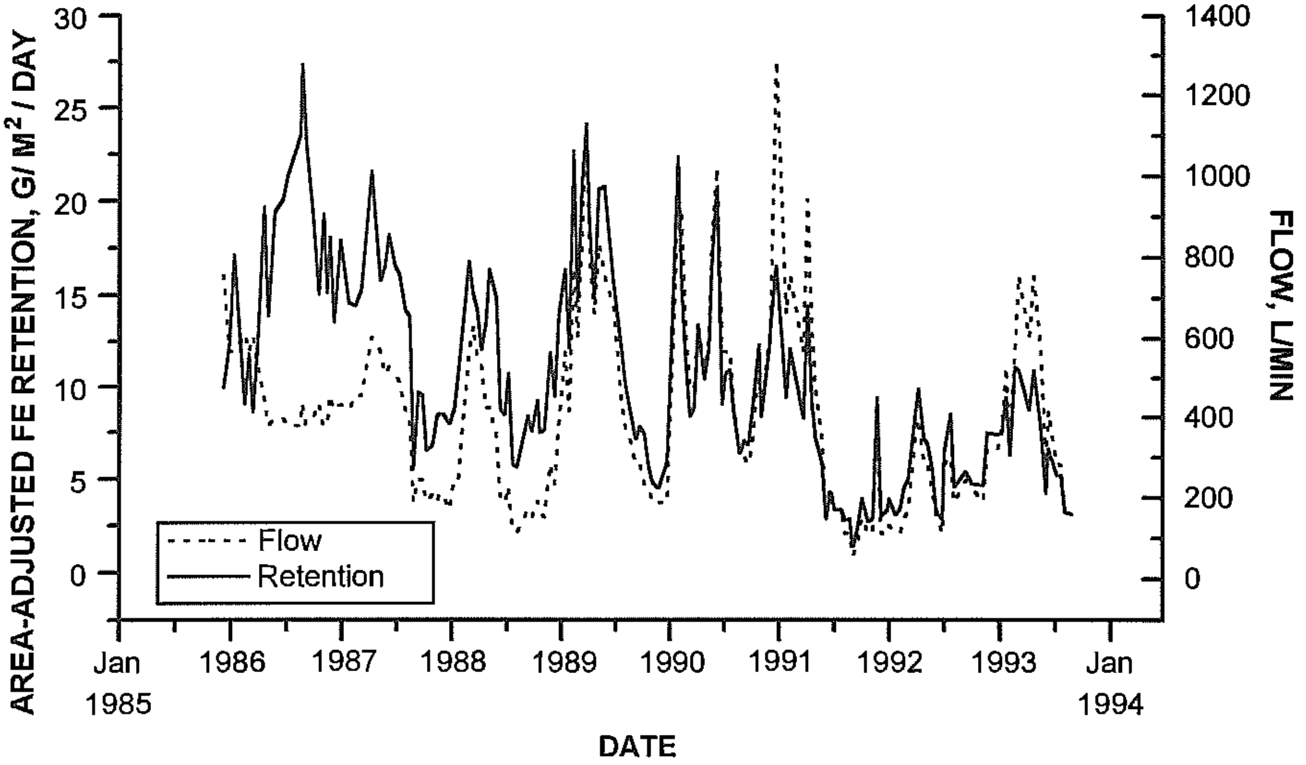

Figure 4. The relationship of area-adjusted iron retention and flow rate at the Simco wetland over the life of the wetland.

Discussion

Is Iron Treatment at Simco Improving With Age?

Evidence indicating that the Simco wetland has improved in its ability to retain iron over its 8-yr history is twofold. First, during the initial few years following installation, frequent chemical treatment of the discharge water from the wetland was necessary. The frequency and duration of chemical treatment has declined as the wetland has aged. Over the last 3½ yr, chemical treatment of the wetland discharge has not been necessary to meet Federal compliance for iron. Water treatment was judged by Ohio authorities as sufficient to warrant the removal of chemical treatment equipment in 1993. In addition, the site was previously declared a national urban wildlife sanctuary in 1990, and the Ohio Division of Wildlife accepted the wetland area as an official natural area in 1993.

Second, treatment efficiency for iron at Simco has improved over time to its current level above 90%. Two measures are commonly used to assess the performance of constructed wetlands with respect to mine water treatment: treatment efficiency and area-adjusted iron retention. We have shown here (and elsewhere, Stark 1990) that treatment efficiency is a better index of wetland performance for iron: the swamping effect of flow rate and iron load on area-adjusted Fe retention makes it an inappropriate evaluative tool (although a valuable design parameter). Iron load at Simco is very strongly positively correlated to area-adjusted Fe retention ($r = +0.88$, $p < 0.001$), such that a knowledge of the load of iron to the wetland explains 80% (r^2) of the observed variation in iron retention. Therefore, the findings that area-adjusted Fe retention at Simco has not changed significantly over the wetland history and has basically fluctuated with flow rate ($r = +0.68$, $p < 0.001$) are not surprising.

Evidence countering the contention that the observed improvement in iron treatment efficiency over time at Simco indicates an age-related wetland phenomenon is also twofold. First, the source water iron concentration has declined with time. From 1986 through 1988, inlet Fe concentration averaged near 125 mg/L. However, since

1991, inlet Fe concentration has averaged less than 100 mg/L. Outlet iron concentration has mirrored inlet iron concentration, such that lower outlet total iron levels are in part a product of lower inlet levels. A correlation of inlet and outlet iron concentration reveals that a strong correlation is present (r = +0.65) and that 43% (r^2) of the variation in outlet Fe is a product of inlet Fe.

Table 2. Pearson product moment correlation coefficients (r) between the two performance indices and a variety of water quality parameters for total iron.

Performance Index	Inlet [Fe]	Outlet [Fe]	Fe load	Flow rate	Treatment efficiency
Inlet [Fe]	—	—	—	—	—
Outlet [Fe]	+0.65**	—	—	—	—
Fe load	+0.31**	+0.70**	—	—	—
Flow rate	-0.23*	+0.29**	+0.82**	—	—
Treatment efficiency	-0.44**	-0.94**	-0.74**	-0.46**	—
Area-adjusted mass retention	+0.41**	+0.54**	+0.89**	+0.68**	-0.53**

*significant at $p<0.01$
**significant at $p<0.001$

Secondly, the addition of a fourth wetland cell at Simco in 1989 is probably at least partly responsible for the increase in treatment efficiency observed at Simco. However, a calculation of the treatment efficiency at Simco using outlet total iron values from Cell 3, rather than from the system outlet, reveals that (1) substantial increases in efficiency occurred in the first 3 yr, (2) efficiency stabilized over the next 3 yr, and (3) efficiency has increased during the last 2 yr. Thus it appears that the oldest three wetland cells improved in their ability to retain iron while becoming established wetlands, and then have, at the very least, maintained a level of retention without declining.

Why Has Simco Improved With Age?

After 8 yr of operation, the Simco wetland has shown no signs of declining iron retention or pH mitigation. This phenomenon is probably due to a variety of factors; several nonexclusive hypotheses are presented below.

Presence of Moderate Mine Water. Although acidity exceeds alkalinity at the source, the pH is near neutrality (6.5) and alkalinity is present in significant concentrations (88 mg/L). Iron concentrations have generally been <100 mg/L, with most of the iron present in the ferrous form. Iron oxidation and precipitation of amorphous iron hydroxides (ferrihydrite) under these conditions are rapid (Ferris et al. 1989). The only water pollutant present is iron. Constructed wetlands have been shown to mitigate iron levels effectively at a variety of pH levels (e.g., Wieder 1989).

Wetland Design and Modifications. The Simco wetland was designed in 1985 to have a bed slope of 1%. This has resulted in a tendency of water to channelize during high flows and/or colonization by muskrats or beavers. To alleviate channelization and decrease the surface water depth in the wetland, the source water was split in 1987, effectively halving the flow rates to each of the upper two cells (fig. 1). Simultaneous with this, a series of straw dikes was installed in each cell (about five per cell), forcing the water to flow gently back and forth within each wetland cell. Following these modifications, treatment efficiency increased substantially for iron. Periodically the straw dikes have been reinforced, and about every 2 yr muskrats or beaver have had to be trapped out of the system in order to maintain the integrity of the study.

The configuration of Simco has proven to be effective in eliminating discharges of iron during the heaviest of summer storms. For example, during a storm lasting 3 days during which 13 cm of precipitation fell, iron concentrations at the NPDES point remained in compliance, despite an outflow rate that exceeded the inflow rate by a factor of 3 during the downpour. We attribute the presence of three ponds downstream of the wetland proper as a positive factor in ensuring effective iron retention during storms (Stark et al. 1994).

The Simco wetland is deeper, both by design and as a result of the aging process, than most constructed wetlands designed to treat iron. Initially, the depth of the compost at Simco was about 50 cm. Direct measurements of compost depth began in 1988 and indicate that substrate depth in the upper three cells has increased to 80 cm through 1993, for an average annual accumulation of 3.75 cm. However, most of this accumulation occurred during

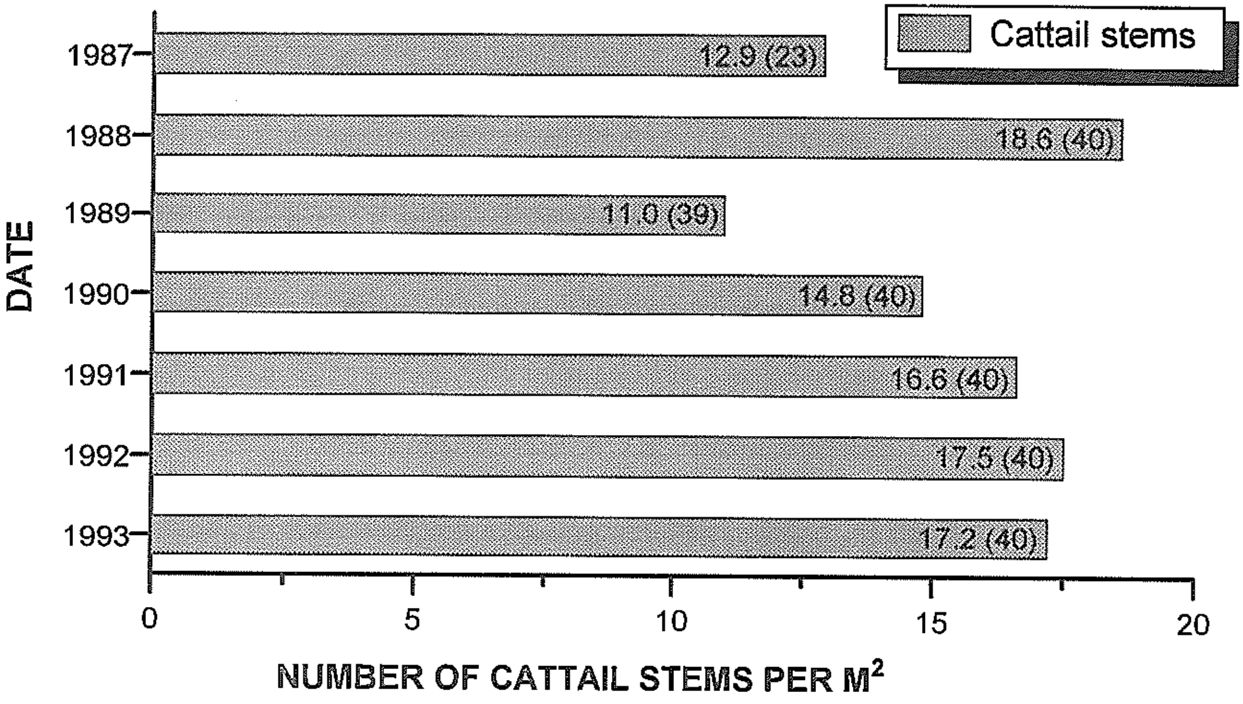

Figure 5. Mean cattail (Typha latifolia) stem density since 1987 at the Simco wetland (n-values in parentheses).

the first 4 yr of operation. The deep substrate creates a deep reducing zone that slowly transforms oxides of Fe into reduced iron (unpublished data). The canyon location assures that the gradual buildup of iron will not diminish treatment by providing a natural freeboard.

Role of Cattails. Cattail density may be related to treatment efficiency: the three highest annual mean treatment efficiencies (1988, 1992, 1993) correspond to the three highest mean cattail densities. The degradation of cattail biomass supplies the ultimate carbon source to the subsurface bacteria in the wetland, suggesting that there should be a lag time between summer density and peak treatment efficiency. However, this was not observed. A dense growth of cattails may result in better water treatment by encouraging a sheet flow rather than channelization, and diffusing the water flow. In addition, cattails remove water through transpiration, decreasing flow rates through the wetland, which should enhance treatment. For example, during the summer months, it is usual for the outflow rate to be 25% less than the inflow rate. Finally, the dense cattail growth may mirror overall temperature-dependent biological and chemical transformations within the wetland.

Vegetation Patterns at Simco

Aside from the anomalous year 1988, cattail density has generally increased each year, becoming fairly stable in 1991. It therefore required six growing seasons for the cattail productivity to reach a stable level at Simco. The timing corresponds roughly to a steady, high treatment efficiency level for iron.

Coverage of non-Typha species, however, has declined from a second summer high of 40% in 1987 to a current level of only 4% in 1993. This decline is principally a result of the surge in growth of Leersia to 22% in 1987, followed by a drop off in Leersia coverage to present levels of <1% in each of 1992 and 1993. There are currently no co-dominant species in the upper three cells: not a single species other than Typha latifolia occupies more than 1% of the wetland surface.

Table 3. Mean percentage cover and species diversity of non-cattail plant and algal species (grouped) at the Simco wetland, Cells 1-3; diversity includes *Typha latifolia*.

Species	1986	1987	1988	1989	1990	1991	1992	1993
Acer sp.	---	---	<1	---	---	---	---	---
Ailanthus altissima	---	<1	---	---	---	---	---	---
Alisma aquaplantago	---	1	<1	5	---	---	---	---
Epilobium sp.	---	1	---	---	---	---	---	---
Equisetum arvense	<1	<1	---	---	---	---	---	---
Impatiens sp.	---	---	---	---	---	<1	---	---
Leersia oryzoides	4	22	11	1	6	4	<1	<1
Lemna minor	4	2	5	1	1	2	1	1
Phalaris arundinacea	<1	2	---	---	---	---	---	---
Phleum pratense	---	---	<1	---	---	---	---	---
Polygonum sagittatum	<1	<1	---	---	---	---	---	---
Salix sp.	<1	---	---	---	---	---	---	---
Spirea sp.	---	---	---	---	---	<1	---	---
Verbena hastata	<1	---	---	---	---	---	---	---
ALGAE:								
Chlamydomonas sp.						---	---	---
Euglena sp.						---	---	---
Microspora sp.						12	---	1
Oscillatoria sp.						---	3	1
Total algae[1]	5	12	3	12	---	12	3	2
Total cover (non-*Typha*)	13	40	19	19	7	18	3	4
Species Diversity	12	13	10	8	7	6	4	5

[1] blanks indicate that individual algal species coverage was not determined prior to 1991.

Species diversity also reached a peak in the second summer (1987), with 13 species present. However, diversity has steadily declined to only five species in 1993. We can assume that the species initially showing up in the wetland were probably planted incidentally along with the cattails. As Kadlec (1989) found in constructed wetlands receiving municipal wastewater, species diversity has declined to favor almost exclusively cattails. The latter author suggested that the constant pollutant load and supply of water works against species diversity and favors pollution-tolerant species. A constructed wetland receiving a steady supply of mine water will seldom "dry down," which is a phenomenon that encourages a variety of plant species to colonize. Rather, conditions are fairly stable with respect to water availability and water quality. Pollutants, in this case iron, are constantly present, providing a strong selection pressure for plant species tolerant of iron concentrations not normally found in natural wetlands. Along the periphery of the Simco wetland, a diverse emergent wetland plant community has developed, but nonetheless colonization of the wetland proper by this shore flora is not occurring.

The decline in non-cattail coverage and species diversity has had no negative effects on iron treatment at Simco. It is apparent that iron treatment is not related to the presence or the abundance of non-Typha species. However, the density of Typha latifolia shoots may be related to improved water treatment for iron; this contention remains to be demonstrated.

Acknowledgments

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