AN EVALUATION OF SUBSTRATE TYPES IN CONSTRUCTED WETLANDS ACID DRAINAGE TREATMENT SYSTEMS

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Abstract--Many wetlands for acid drainage treatment have been constructed by the coal and utility industries with limited information on design and operating criteria. To investigate important components (substrates, vegetation, microbes) in wetlands treatment systems, the Tennessee Valley Authority (TVA) initiated experiments at the Acid Drainage Wetlands Research Facility, Jackson County, Alabama, in September 1986. All substrates (6) provided significant treatment of dissolved iron, suspended solids, and pH. Acid wetland soil was initially more efficient but differences between substrates became insignificant by fall. Only limited manganese removal occurred. The pronounced pattern of removal efficiency improvement, common to all substrate types, suggested that the plant-soil-microbial complex important to acid drainage treatment developed within all tested substrates within one year. Treatment differences between substrates were inadequate to justify added costs of deliberately installing a specific substrate in operating systems; slightly better performance of acid wetland soil supported protecting existing wetlands at construction sites.

INTRODUCTION

Acid water drainage (pH<6, Fe>4, Mn>2), from coal mining, processing, transporting, storage, and burning lowers water quality, impacts aquatic biota, and jeopardizes drinking water supplies throughout the eastern United States. Conventional treatment technology consists of grading and recontouring to reduce or divert flows and addition of alkaline solutions to elevate pH levels and chemically precipitate metallic ions. Land reforming is almost prohibitively expensive, and chemical treatment is not only expensive but often requires a long-term maintenance and operational commitment. Constructed wetlands appear to offer an inexpensive, self-maintaining, long-term solution that may be applicable to small or large flow acid discharges (Brodie et al. 1986, 1987). In addition to others in the coal and utility industry, the Tennessee Valley Authority (TVA) has established

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11 wetland treatment systems at coal mines, coal preparation plants, and coal-fired plants (Brodie et al 1988).

Several investigations have suggested or demonstrated the effectiveness of wetlands in removing acidity, sulfate, iron, manganese, and other pollutants from acid mine drainage (Holm 1983, Pesavento 1984, Weider et al. 1984, Brodie et al. 1987). Some have described failures of demonstration wetlands to achieve desired results (Pesavento 1984, Weider et al. 1985).

Laboratory studies have explored design and operational parameters of wetlands for acid mine drainage treatment (Tarleton et al. 1984, Gerber et al. 1985). Little work has been done on pollutant removal mechanisms of wetlands for mine drainage treatment. Physical/chemical mechanisms may be important, but vegetative and microbiological mechanisms are thought to be the major factors in pollutant removal. Results of various treatment systems have ranged from poor to excellent, and more importantly, few systems have been studied over long time periods (Pesavento 1984, Weider et al. 1984). Competitive advantages of man-made wetlands over chemical treatment are based not only upon short-term economics but upon internal maintenance attributes of wetlands systems that suggest long-term independent functioning of stabilized systems.

TVA's Acid Drainage Wetlands Research Facility (ADWRF) was established for controlled, pilot-scale experiments at an active seep to investigate optimal size, type, and operational longevity of wetlands systems for removing various pollutants from acid drainage. Initiated in September 1986, the first phase is designed to identify most efficient substrate type(s). Future studies will compare removal efficiencies of different wetlands macrophytes and identify important microbial populations (bacteria, fungi, algae, and protozoa) and optimal environmental conditions for water quality improvement.

METHODS

In August 1986, a series of cells, piping, and associated hardware comprising the Acid Drainage Wetlands Research Facility, was assembled at TVA's Fabius Coal Mine Site, Jackson County, Alabama. Each of the 20 cells consisted of a buried, half-round, fiberglass culvert 6.3 m (20 ft) long and 1.1 m (42 in) in diameter (Figure 1). An unlined pond in spoil material

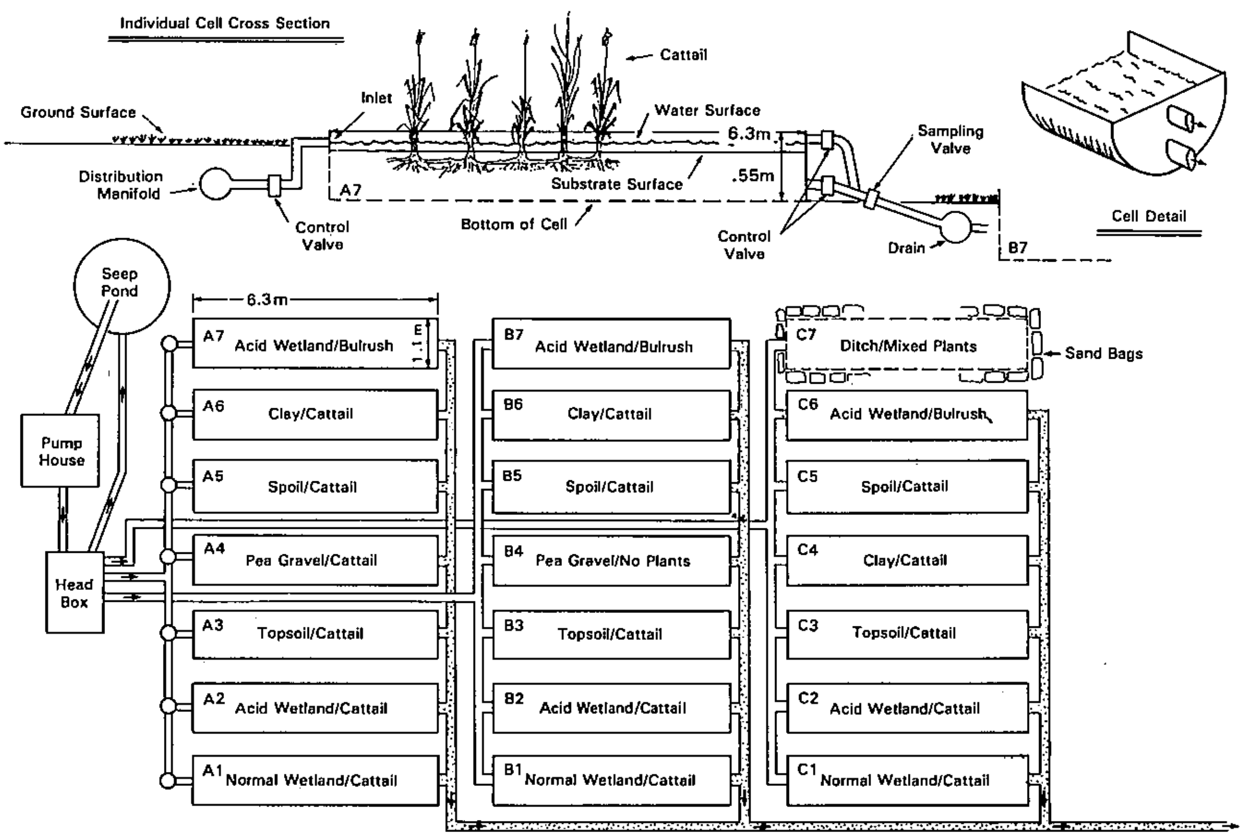

Figure 1. TVA's Acid Drainage Wetlands Research Facility, Jackson County, Alabama - Phase 1 Experiment comparing treatment among substrate types.

was planted with marsh/wet meadow vegetation. Pond and pea gravel cells served as controls.

Water from a mine seep was pumped into a head box and gravity discharged into each cell. A polyvinylchloride pipe collection system discharged into a field scale wetlands treatment system and thence to a stream. Appropriate valving provided flow control to each cell. Seep water had a pH of 5.9 s.u., with 37 mg/L iron, and 16 mg/L manganese.

Substrates

Clay was obtained from the B soil horizon at an undisturbed site near the facility. Mine spoil was obtained on site. Pea-gravel was purchased from a river gravel operation. Topsoil consisted of soil from the A horizon from nearby agricultural fields. Acid wetland consisted of substrate from a natural wetland below an acid seep nearby. Natural wetland consisted of substrate from a nearby natural wetland without acid drainage.

Samples of each substrate type (except topsoil) were analyzed for standard soil composition and chemistry parameters (Table 1). After planting, ten times the desired level of 0.32 kg of 6-12-12 fertilizer was inadvertently placed in each cell resulting in an equivalent rate of 4638 kg/ha (4097 lb/acre).

Vegetation

Initial evaluations (1987-1989) were designed to test cattail (*Typha latifolia*) with bulrush (*Scirpus cyperinus*) planted in three cells. Planting material was obtained from nearby wetlands unimpacted by mine drainage. Vegetative material was washed to remove soil, cut to standard stem length of 30 cm, and weighed before planting.

Fifty-seven cattail, average total weight of 6,132 g, were planted on 30 cm centers in three rows of 19 plants in 16 cells on 2 September 1986. Three cells were similarly planted to bulrush, average total weight of 10,639 g, on 4 September. Stem densities and heights were periodically measured throughout the study.

Monitoring

Relatively high flow rates to each cell (1.0 L/min) were established on 18 September 1986 then reduced to 0.5 L/min on 20 December 1986 to accelerate development of differential treatment results. Individual cell flow rates were measured, recorded, and adjusted daily.

Weekly (29 September - 5 November 1986) or twice monthly (after 5 Nov.) inflow water samples, obtained from the manifolds, and outflow samples from the

Table 1. Composition of five substrate types tested at the Fabius Acid Drainage Wetlands Research Facility, Jackson County, Alabama.

	Substrate Types				
Soil Parameters	Natural Wetland	Acid Wetland	Clay	Mine Spoil	Pea Gravel
Organic matter (%)	0.6	0.9	0.5	0.1	1.3
Phosphorus (mg/L)	5.0	6.0	2.0	3.0	1.0
Potassium (mg/L)	94.0	98.0	72.0	67.0	1.0
Magnesium (mg/L)	114.0	80.0	29.0	37.0	1.0
Calcium (mg/L)	650.0	290.0	40.0	20.0	4.0
Sodium (mg/L)	11.0	17.0	9.0	10.0	4.0
pH (mg/L)	7.0	4.4	5.1	4.8	5.7
Nitrate (mg/L)	4.0	4.0	4.0	6.0	1.0
Sulfur (mg/L)	30.0	384.0	41.0	131.0	26.0
Zinc (mg/L)	2.4	7.0	0.9	2.1	0.3
Manganese (mg/L)	122.0	45.0	9.0	6.0	1.0
Iron (mg/L)	94.0	138.0	20.0	8.0	1.0

upper level of each cell were analyzed for pH, temperature, dissolved oxygen, conductivity, total suspended solids (TSS), oxidation-reduction potential, total and dissolved iron (Fe), total and dissolved manganese (Mn), ferrous iron, aluminum, and sulfate. Sample collection and analysis by the TVA laboratory followed standard procedures (US EPA 1979). A two-way analysis of variance (ANOVA) with a Ryan-Einot-Gabriel-Welsch multiple F-test and paired t-tests (SAS 1985) were used in data analysis.

DISCUSSION AND CONCLUSIONS

Since these results represented only the first year of operation of the ADWRF, the statistical analyses were limited to those parameters most important to operational permit discharge limits, i.e., pH, dissolved Fe and Mn, and TSS for the period 14 Jan to 9 Sept 1987.

All substrate types significantly reduced dissolved Fe and TSS and increased pH levels (table 2). Effluent concentrations of dissolved Fe ranged from 4.8 mg/L (acid wetland/cattail) to 7.2 mg/L (topsoil/cattail) (table 3). Total suspended solids in cell effluents ranged from 13.9 mg/L (acid wetland/cattail) to 14.5 mg/L (natural wetland/cattail). Variation in effluent pH values was lower, ranging from 6.2 s.u. (natural acid wetland/cattail) to 6.4 s.u. (topsoil/cattail). Effluent values for dissolved Mn, ranging from

Table 2. Comparisons of influent-effluent concentrations of Fe, Mn, TSS, and pH between 6 replicated substrates from Jan 14-Sept 9, 1987, at the Fabius Acid Drainage Wetlands Research Facility, Jackson County, Alabama (paired t-test, 0.05, SAS, 1985).

Substrate/Vegetation	N	Mean Effluent Concentration (mg/L)	Prob>'t'
	Influent 32.3 mg/l		Dissolved Iron
Topsoil/Cattail	57	7.2	<0.0001
Natural Wetland/Cattail	57	6.1	<0.0001
Clay/Cattail	57	5.6	<0.0001
Acid Wetland/Bulrush	57	5.4	<0.0001
Mine Spoil/Cattail	57	5.3	<0.0001
Acid Wetland/Cattail	57	4.8	<0.0001
	Influent 14.8 mg/l		Dissolved Manganese
Natural Wetland/Cattail	57	14.5	0.254
Clay/Cattail	57	14.3	0.007
Mine Spoil/Cattail	57	14.3	0.006
Topsoil/Cattail	57	14.2	0.006
Acid Wetland/Bulrush	57	14.1	0.038
Acid Wetland/Cattail	57	13.9	0.076
	Influent 32.1 mg/l		Total Suspended Solids*
Topsoil/Cattail	55	16.6	0.008
Clay/Cattail	55	13.6	0.004
Acid Wetland/Cattail	55	12.2	0.001
Mine Spoil/Cattail	55	12.1	0.0006
Natural Wetland/Cattail	55	12.1	0.002
Acid Wetland/Bulrush	55	11.8	0.001
	Influent 5.9 s.u.		pH**
Topsoil/Cattail	56	6.4	0.0001
Acid Wetland/Bulrush	52	6.3	0.0001
Clay/Cattail	54	6.3	0.0001
Mine Spoil/Cattail	53	6.3	0.0001
Natural Wetland/Cattail	54	6.2	0.0001
Acid Wetland/Cattail	53	6.2	0.0001

*Two influent (and corresponding effluent) values over 400 mg/l were excluded from the analysis.
**pH values over 7.5 were excluded from the analysis.

Table 3. Effect of substrate type on effluent concentrations of dissolved Fe and Mn, TSS, and pH from Jan 14-Sept 9, 1987, at the Fabius Acid Drainage Wetlands Research Facility, Jackson County, Alabama (multiple F test, SAS, 1985). Mean effluent values connected by a continuous line are not significantly different.

	Mean Effluent Concentration (mg/L)	N	Wetland Type
Dissolved Iron (mg/l)	5.5	52	Topsoil/Cattail
	5.2	54	Clay/Cattail
	5.1	53	Natural Wetland/Cattail
	4.8	54	Mine Spoil/Cattail
	4.7	54	Acid Wetland/Bulrush
	4.6	53	Acid Wetland/Cattail
Dissolved Manganese (mg/l)	14.3	53	Natural Wetland/Cattail
	14.2	54	Mine Spoil/Cattail
	14.1	54	Clay/Cattail
	14.0	52	Topsoil/Cattail
	14.0	53	Acid Wetland/Cattail
	13.9	54	Acid Wetland/Bulrush
Total Suspended Solids (mg/l)	13.7	52	Topsoil/Cattail
	11.8	54	Clay/Cattail
	11.2	53	Acid Wetland/Cattail
	10.7	54	Mine Spoil/Cattail
	10.2	53	Natural Wetland/Cattail
	10.0	54	Acid Wetland/Bulrush
pH (standard units)	6.4	51	Topsoil/Cattail
	6.3	51	Clay/Cattail
	6.3	49	Acid Wetland/Bulrush
	6.3	50	Mine Spoil/Cattail
	6.3	50	Natural Wetland/Cattail
	6.2	49	Acid Wetland/Cattail

13.9 mg/L (acid wetland/cattail) to 14.5 mg/L (natural wetland/cattail), tested significantly different (4 of 6 substrates) from influent values (14.8 mg/L) but absolute removal values were very low and statistical significance was inconsequential.

Seasonal comparisons of effluent values revealed that acid wetland/cattail significantly reduced dissolved Fe during winter (Jan-Feb) but other seasonal differences (Mar-Sept) in Fe or in other parameters were unclear.

Examination of the results for these parameters over time exposes a strong temporal pattern in removal efficiencies for all substrate/plant treatment types that was obscured by overall influent/effluent means (Figures 2-5). Declines in influent Fe and Mn concentrations, a concomittant increase in pH and extremely variable TSS values during the study period are unexplained, though possibly related to regional drought conditions.

Effluent values for TSS, dissolved Fe, and Mn suggested that low removal efficiencies during the first winter may have been due to (1) system initiation in late fall and (2) overloading during the first 10 weeks of operation. At an application rate of 0.5 L/min, efficiency improved but leveled off until warmer weather in early February. Removal efficiency gradually improved until mid April and rapidly thereafter. The pronounced pattern, common to all substrate types, suggested that microbial populations increased dramatically with warmer temperatures from mid February onward and renewed plant growth in April developed system capability to remove much of the Fe from the acid drainage influent. Results from the pea gravel cell showed similar but more variable declines in Fe content, Figure 2.

Since the effluent results are not statistically significant between substrates, the removal efficiency improvement pattern common to all experimental cells suggests a major biological component in the removal process. The plant-substrate-microbe complex that is important to water quality improvement will develop, without innocula, in the 6 substrates tested to date, indicating the ubiquitous nature of desirable microbial organisms in wetlands treatment systems (Gregory and Staley 1982).

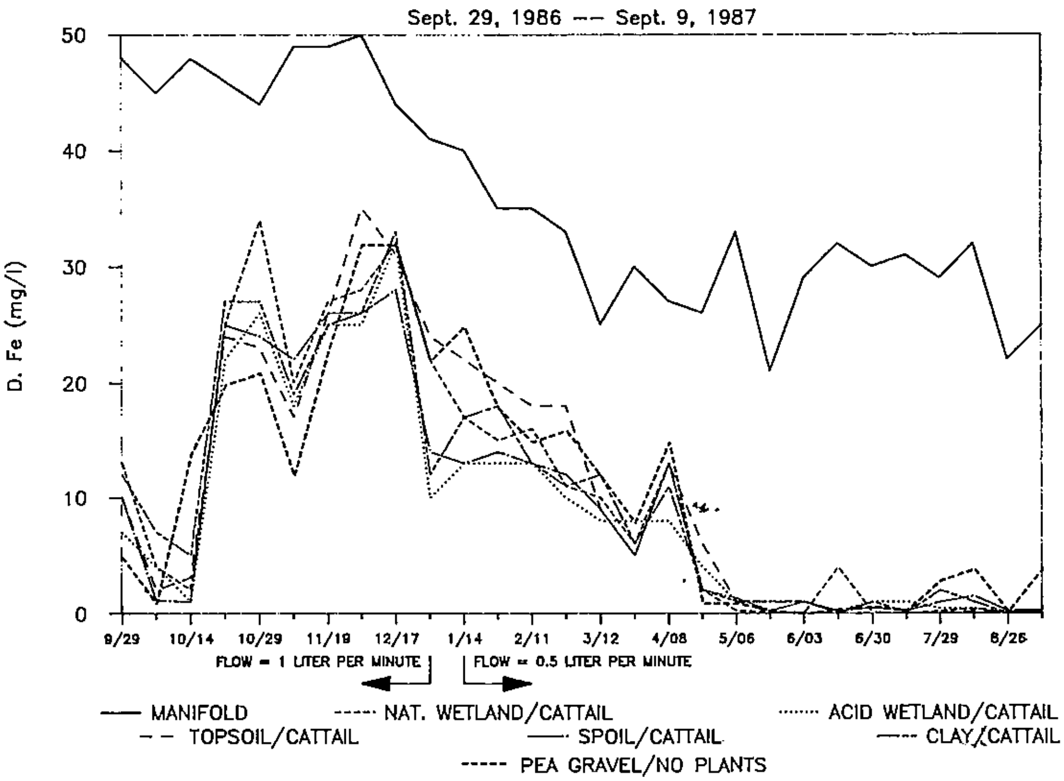

Figure 2. Effect of substrate type on dissolved iron in tests conducted at the Acid Drainage Wetlands Research Facility. Broken lines represent means of three replicated wetland cells, and solid line represents mean influent concentrations (manifold).

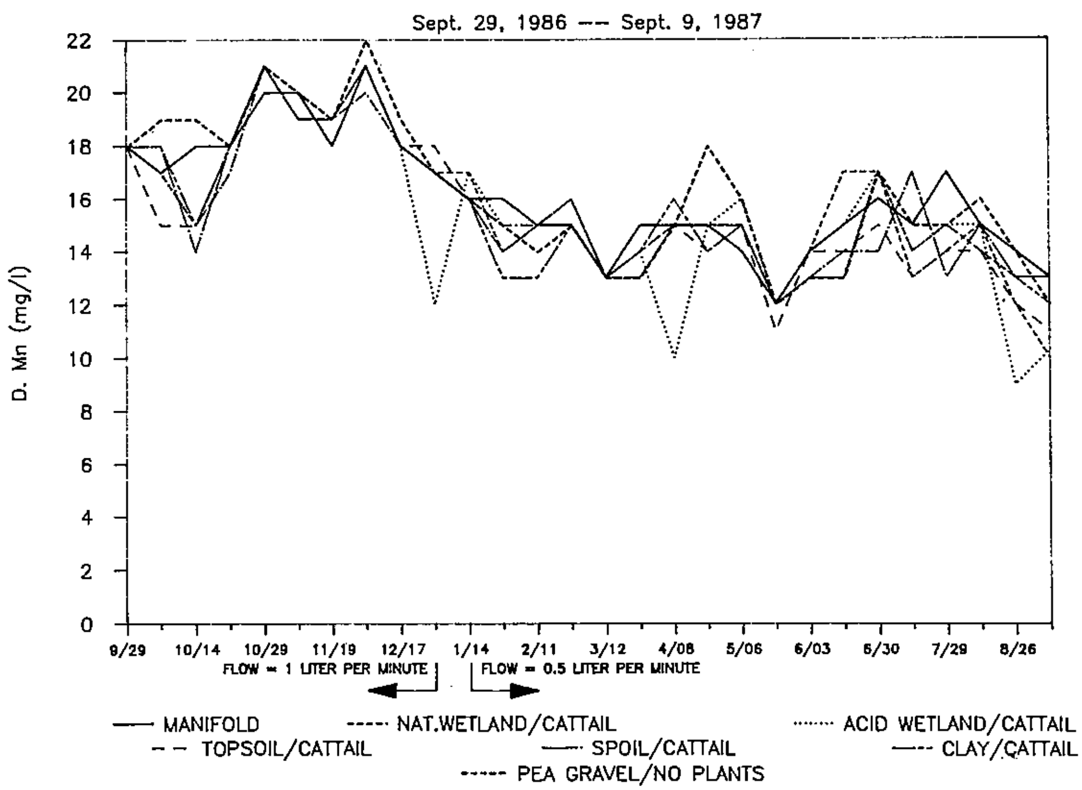

Figure 3. Effect of substrate type on dissolved manganese in tests conducted at the Acid Drainage Wetlands Research Facility. Broken lines represent means of three replicated wetland cells, and solid line represents mean influent concentration (manifold).

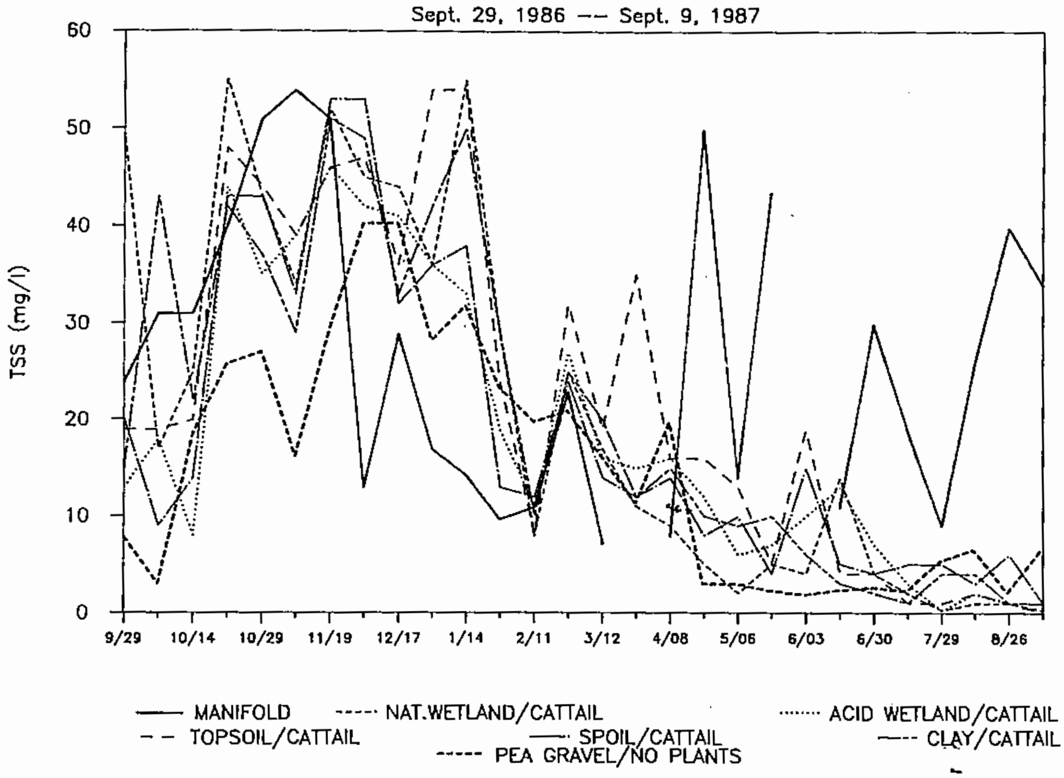

Figure 4. Effect of substrate type on total suspended solids in tests conducted at the Acid Drainage Wetlands Research Facility. Broken lines represent means of three replicated wetland cells, and solid line represents mean influent concentration (manifold).

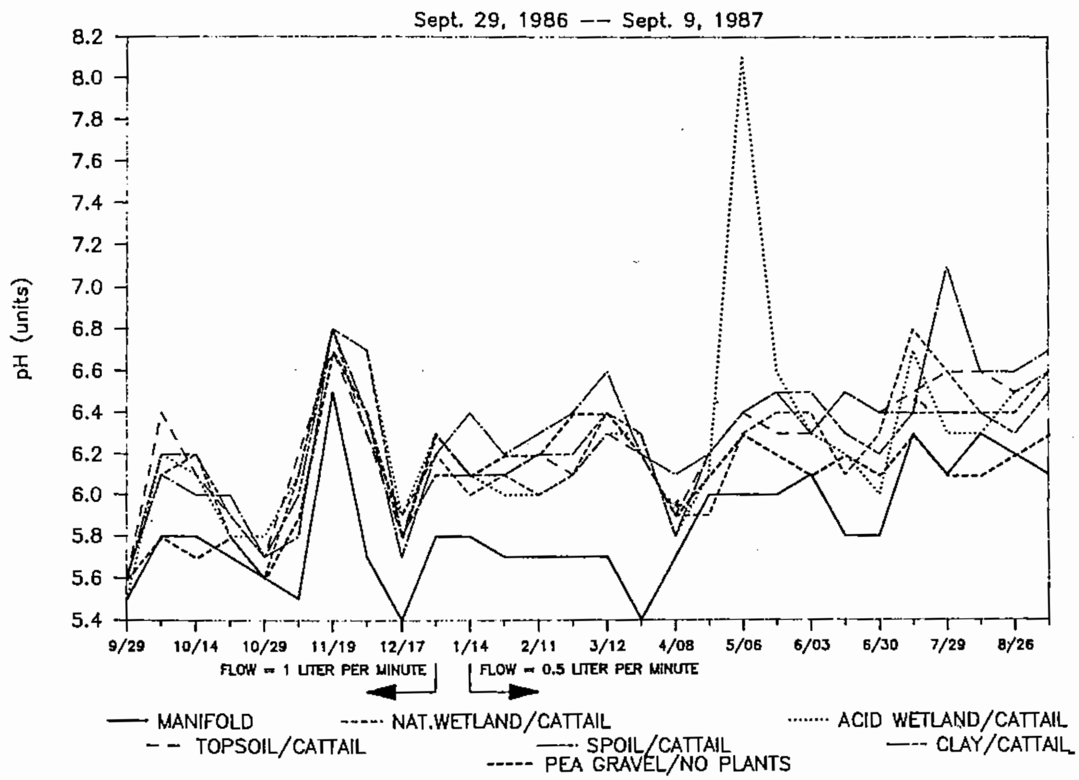

Figure 5. Effect of substrate type on pH in tests conducted at the Acid Drainage Wetlands Research Facility. Broken lines represent means of three replicated wetland cells, and solid line represents mean influent concentration (manifold).

Relatively poor removal of Mn, even at the end of the growing season compared to much greater removal in many operational systems (Brodie et al. 1988) suggested that the plant-soil-microbial complex does not substantially alter dissolved Mn compounds until after dissolved Fe is relatively low or unavailable for microbial metabolism. A lower influent application rate resulting in better dissolved Fe removal is likely to result in improved treatment of dissolved Mn.

Variations in influent and effluent pH seemed closely related although a similar gradual improvement over time was apparent. In contrast, a strong pattern of improved removal of TSS over time was evident despite widely varying influent values.

Though trends for pH and dissolved Mn are not readily apparent, substantial and consistent reductions in dissolved Fe and TSS even though influent values showed considerable variation, suggest that the plant-soil-microbial complex in wetlands treatment systems is amenable to considerable fluctuation in loading rates.

Interpretation of absolute effluent values in terms of wetland treatment system efficiencies must incorporate the application rates in use during these studies. A high application rate (0.5 L/min, ca 500 ft^2/gal/min, 0.4 m^2/mg Fe/min, Brodie et al. 1988) was deliberately selected to accentuate differences, if any, among different substrate types. Valve imprecision caused daily average flows to vary from 0.34 to 0.43 L/min compared to desired rates of 0.5 L/min. Acid and normal wetland substrates inadvertantly had higher flow (application) rates. Since these rates are substantially greater than recommended rates employed at 11 operating treatment systems (Brodie et al. 1988), these results must not be extrapolated to field scale operating systems.

In addition, cattail growing in all substrate types exhibited atypical root growth above the substrate and within the water column around each stem that was not present in operating wetland treatment systems. Visual inspection also revealed a consistent pattern of more vigorous stem and leaf growth in the upper portion of each cell as compared to the middle or lower portions.

Comparison of the average number of cattail stems from new shoots present at four times during the study revealed normal increases throughout the growing season but did not show significant differences between substrate types (Figure 6). Similarly, little differ-

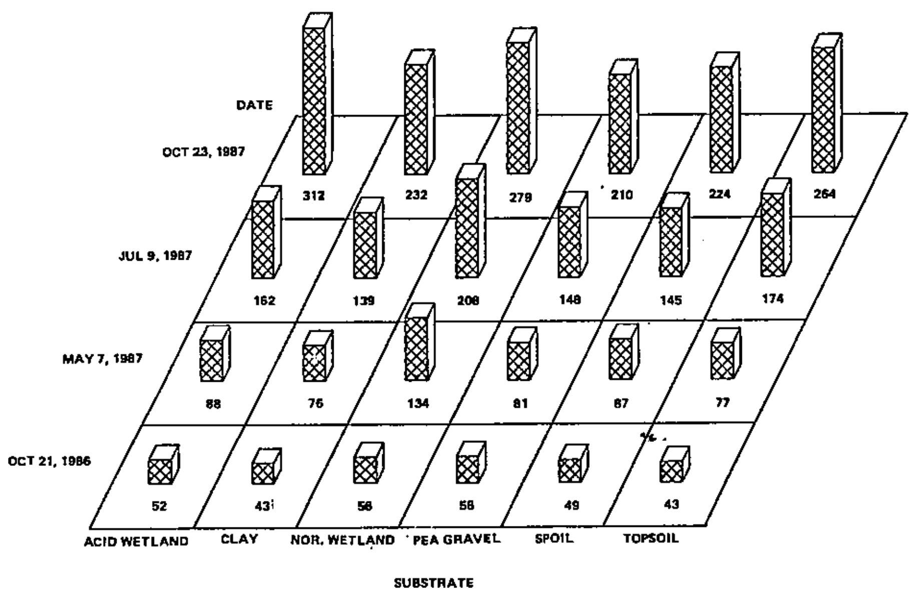

Figure 6. Mean number of cattail stems in experimental cells at the Acid Drainage Wetlands Research Facility, Jackson County, Alabama. One-way ANOVA's on each date showed no significant differences among replicated (3 cells) substrate types.

ence was apparent in height of cattail grown in different substrate types, though topsoil was a significantly better growth medium than pea gravel in July and significantly better than spoil and pea gravel in October. Analysis of phosphorus, total nitrogen and NH_3/NO_3 nitrogen showed considerably more nitrogen content in the water in the upper portion of each cell and a similar difference in phosphorus and total nitrogen in cattail stems and leaves (Table 4).

Within-cell differences in cattail vigor appeared related to available nitrogen and phosphate in seep water and relatively low concentrations in substrate types. Excess fertilizer applied at initiation may have flushed out leaving influent seep water as the principal source for important plant nutrients resulting in atypical root growth in the water column. Since all cells exhibited atypical root growth and differences in cattail vigor were greater within each cell than between cells, these variables were unlikely to have differentially influenced the comparison of removal efficiencies in substrate types.

In summary, our results suggested (1) that substrate type is relatively unimportant to removal treatment efficiency since the desired plant-substrate-microbe complex became established in each type; (2) that microbial innocula were unnecessary; and (3) that vegetation may substantially improve treatment efficiency. From a practical standpoint, substantial

Table 4. Nutrients in water and sediment (October 10, 1987) and cattails (October 16, 1987) in three experimental wetland cells at the Acid Drainage Wetlands Research Facility, Jackson County, Alabama.

Wetland Cell	Location in Cell	Water (mg/L)	Sediment (mg/kg)	Cattail mg/kg dry wt)
		Total Phosphorus		
A5	upper	0.01	170	420
A5	middle	0.02	280	320
A5	lower	0.03	180	260
B6	upper	0.01	240	520
B6	middle	0.05	400	320
B6	lower	0.03	120	200
C5	upper	<0.01	350	960
C5	middle	0.01	240	400
C5	lower	0.02	170	320
		Total Kjeldahl Nitrogen		
A5	upper	0.20	330	4900
A5	middle	<0.02	310	3740
A5	lower	<0.02	310	2720
B6	upper	0.20	430	5810
B6	middle	<0.02	430	1980
B6	lower	<0.02	310	2780
C5	upper	0.16	340	7880
C5	middle	<0.02	360	3380
C5	lower	<0.02	250	4870
		Ammonia Nitrogen/Nitrate Nitrogen		
A5	upper	0.51/0.02	--	--
A5	middle	<0.01/0.01	--	--
A5	lower	<0.01/<0.01	--	--
B6	upper	0.51/0.02	--	--
B6	middle	0.01/0.02	--	--
B6	lower	0.01/0.01	--	--
C5	upper	0.50/0.03	--	--
C5	middle	<0.01/0.02	--	--
C5	lower	<0.01/0.01	--	--

differences must exist between substrate removal efficiencies to justify the considerable construction costs entailed in deliberately installing a specific substrate in field scale operating systems.

The functional values of wetlands vegetation previously identified from operating system results were supported by analysis of these data, i.e., substrates with emergent vegetation had higher removal efficiencies than substrates lacking vegetation. A better understanding of wetlands vegetation is anticipated from the results of future comparisons of removal efficiencies of different wetlands vegetation at the Acid Drainage Wetlands Research Facility.

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