A SURVEY OF CONSTRUCTED WETLANDS FOR ACID COAL MINE DRAINAGE TREATMENT IN THE EASTERN UNITED STATES

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Abstract: The oxidation of pyritic minerals, exposed to oxygen and water during the mining of coal, results in the formation of acid mine drainage (AMD), which is characterized by low pH and high concentrations of dissolved sulfate, iron, and other metals. Federal and State regulations require that discharges from coal surface mines meet water quality criteria. Toward that end, chemical treatment of AMD, usually with soda ash briquettes, lime, limestone, or sodium hydroxide, is effective but expensive. Recently, man-made wetlands have been proposed as a low-cost, low-maintenance alternative to chemical treatment of AMD. To assess the status of man-made wetland treatment of AMD in the eastern U.S., a survey was conducted by the U.S. Office of Surface Mining, Reclamation, and Enforcement. As of May 1988, 142 wetlands had been constructed for AMD treatment. In 50% of the constructed wetlands, treatment efficiencies (reductions in concentration) for H^+, acidity, Fe, Al, Mn, and SO_4^{2-} of at least 68, 67, 81, 48, 34, and 8%, respectively, were obtained. However, over 11% of the constructed wetlands yielded greater concentrations in the effluent from the wetland than were present in the influent AMD for one or more of these 6 chemical parameters. Treatment efficiency generally was not correlated with design criteria (e.g., area of wetland, depth of the organic substrate in the wetland, AMD flow rate, metal loading rates). Also, treatment efficiency was generally not affected by either the type of organic substrate used in wetland construction or the addition of lime and/or fertilizer to the constructed wetland. The effectiveness of wetland treatment of AMD is not only extremely variable, but also presently not predictable.

Key Words: acid mine drainage, constructed wetlands, pollution, water quality.

INTRODUCTION

The mining of coal involves the physical disruption of soil and bedrock, often exposing previously buried pyrite-bearing strata to oxygen and water. Both abiotic and biotic oxidation of these newly exposed pyrite minerals (e.g., pyrite and marcasite) generates acid mine drainage (AMD) that is characterized by low pH (sometimes as low as 2.5) and high concentrations of dissolved iron and sulfate (Colmer and Hinkle 1947, Appalachian Regional Commission 1969, Singer and Stumm 1970). The acidity of the resulting waters can dissolve minerals that are stable under ambient pH conditions, so that AMD may also have high concentrations of dissolved Ca and Mg, as well as other more problematic solutes including Al, Mn, Zn, Cu, and Ni (Barton 1978). As of 1969, about 12,000 km of streams and 12,000 ha of impoundments in the Appalachian coal mining region were seriously affected by AMD (Appalachian Regional Commission 1969).

With the enactment of the Surface Mining Control and Reclamation Act (SMCRA) in 1977, the Office of Surface Mining, Reclamation, and Enforcement (OSMRE) was created within the U.S. Department of the Interior as the Federal agency responsible for regulating coal surface mining and reclamation throughout the United States. As a comprehensive land-use law, SMCRA mandates thorough planning of a mining operation prior to the initiation of actual mining activity. In applying to OSMRE or an approved State regulatory agency for a permit for the surface mining of coal, a potential operator must provide information concerning how the mining activity will be conducted and a plan for restoring the affected land to a condition capable of supporting its pre-mining land uses. In addition, SMCRA requires that before any coal mining activity can begin, a reclamation bond must be posted. The reclamation bond ensures that the mined lands will be adequately reclaimed if the operator is either unwilling or unable to do so. Bonds are typically released in stages after certification that specific reclamation criteria have been satisfied.

Under SMCRA, all areas permitted for coal surface mining activity must be surrounded by ditches designed to divert runoff into sediment/treatment ponds prior to discharge from the mine site. Thus, SMCRA requires coal operators to create point-source discharges. The Federal Clean Water Act (enacted 1972) mandates that all such point-source discharges meet water quality standards set by the U.S. Environmental Protection Agency, including standards for pH (pH must fall between 6 and 9), Fe (concentrations must be less than 7 mg/L daily and less than 3.5 mg/L on a monthly average), and Mn (concentrations must be less than 4 mg/L daily and less than 2 mg/L on a monthly average). State regulatory agencies may set more stringent standards.

To meet the water quality standards, drainage from a coal surface mine collected in the sediment/treatment ponds often must be chemically treated prior to discharge. Commonly used chemicals include soda ash briquettes, hydrated lime, limestone, or sodium hydroxide, all of which raise pH levels, thereby causing the abiotic precipitation of previously dissolved metals. Such chemical treatment can be quite costly, not only during mining, but also potentially after mining has ceased, since any post-mining discharges with unacceptable water quality must continue to be treated. Moreover, final bond release is not granted if, within the permitted area, there is a water source with unacceptable water quality.

Reports from field sites in which the chemistry of AMD improved upon passage through naturally occurring wetlands (Huntsman *et al.* 1978, Wieder and Lang 1982) led to an increased interest in the potential for constructed wetland systems as a low cost, low maintenance alternative to costly chemical treatment of AMD. The published proceedings of recent conferences (Burris *et al.* 1984, Brooks *et al.* 1985, U.S. Bureau of Mines 1988, Hammer 1989) collectively provide a reasonably complete and current overview of the biological and chemical processes in wetlands that may contribute to AMD amelioration. Also evident from these conferences is that while some constructed wetlands have been at least somewhat effective in improving the chemistry of AMD, others have not. Reliable design criteria that can provide *a priori* prediction of the effectiveness of a constructed wetland treatment system in treating a given flow and chemistry of AMD are currently not available.

In light of the uncertainty surrounding the effectiveness and design of constructed wetlands for treating AMD, OSMRE stated its position on constructed wetlands for AMD treatment in a Directive issued in October 1988 (OSMRE 1988). Since OSMRE does not specify how a coal operator achieves compliance with water quality criteria, the operator may choose a constructed wetland treatment system instead of a more conventional chemical treatment system. However, if the constructed wetland fails to produce a discharge with acceptable water quality, some other proven method of water treatment must be initiated. Water quality criteria also apply to any post-mining discharges from the permitted area. After mining activity has ceased, any discharges with unacceptable water quality must continue to be treated. Regardless of the treatment method (constructed wetland versus conventional chemical treatment), the existence of post-mining discharges with unacceptable water quality will preclude final bond release. In all respects, OSMRE's position views constructed wetland treatment of AMD as no different from conventional chemical treatment of AMD.

As a result of the increasing interest in constructed wetlands for AMD treatment, OSMRE conducted a survey of all such systems on active coal surface mines east of the Mississippi River. In synthesizing the information obtained from the OSMRE survey, this paper has several objectives: to identify the types of AMD for which constructed wetland treatment systems have been installed, to summarize design and construction methodologies for constructed wetland treatment systems, to assess the overall effectiveness of constructed wetlands for AMD treatment, and to try to identify factors that may influence the effectiveness of constructed wetlands for AMD treatment.

THE SURVEY

As mandated by SMCRA, OSMRE either directly regulates the surface mining of coal or oversees the operations of an approved State regulatory program. In either capacity, through permitting, inspection, and enforcement activities, OSMRE should be aware of any wetland constructed on an active coal surface mine for the purpose of AMD treatment. As such, an OSMRE-directed survey of constructed wetlands for AMD treatment should represent a complete census of such wetlands. Also included in the survey were some wetlands that had been constructed for AMD treatment on abandoned mine lands, i.e., areas that either were mined prior to the enactment of SMCRA, or on post-SMCRA sites where unacceptable water quality developed on the site some time after the reclamation bond had been released.

In January 1988, survey forms were distributed through the OSMRE field offices in the eastern United States. For each constructed wetland system, information was requested regarding date of construction, wetland location, wetland design, flow and chemistry of the influent and effluent water, and whether or not additional conventional chemical treatment was used in conjunction with the constructed wetland system. All survey forms were completed by OSMRE and/or State regulatory personnel and returned to OSMRE's Eastern Field Operations, Pittsburgh, PA. As much as was possible, information reported on the forms was verified and/or clarified through telephone conversations, but for many sites, some information was either missing or unavailable. Reported information generally was not verified by field visitation.

Much of the discussion and interpretation of the results of the survey are based on statistical analyses (simple correlations, Kruskal-Wallis tests, SAS 1982) carried out on reported water chemistry. For each site, chemical concentrations for the AMD flowing into the wetland and for the water leaving the wetland were reported as single values, and it was often unclear whether the reported values represented individual samples, short-term means, or long-term means. Regardless, certain but unreported variability in water chemistry at each site was not taken into account by the survey.

DESCRIPTIVE INFORMATION

Of the 159 field sites for which information was obtained, 17 either did not include a constructed wetland or included a constructed wetland that was not intended for water quality improvement. Thus, as of May 1988 a total of 142 wetlands had been constructed to treat AMD east of the Mississippi River. Most were installed between 1985 and 1987 (Figure 1A), and by far, the majority were located in Pennsylvania (Figure 1B). Neither of these findings is surprising since

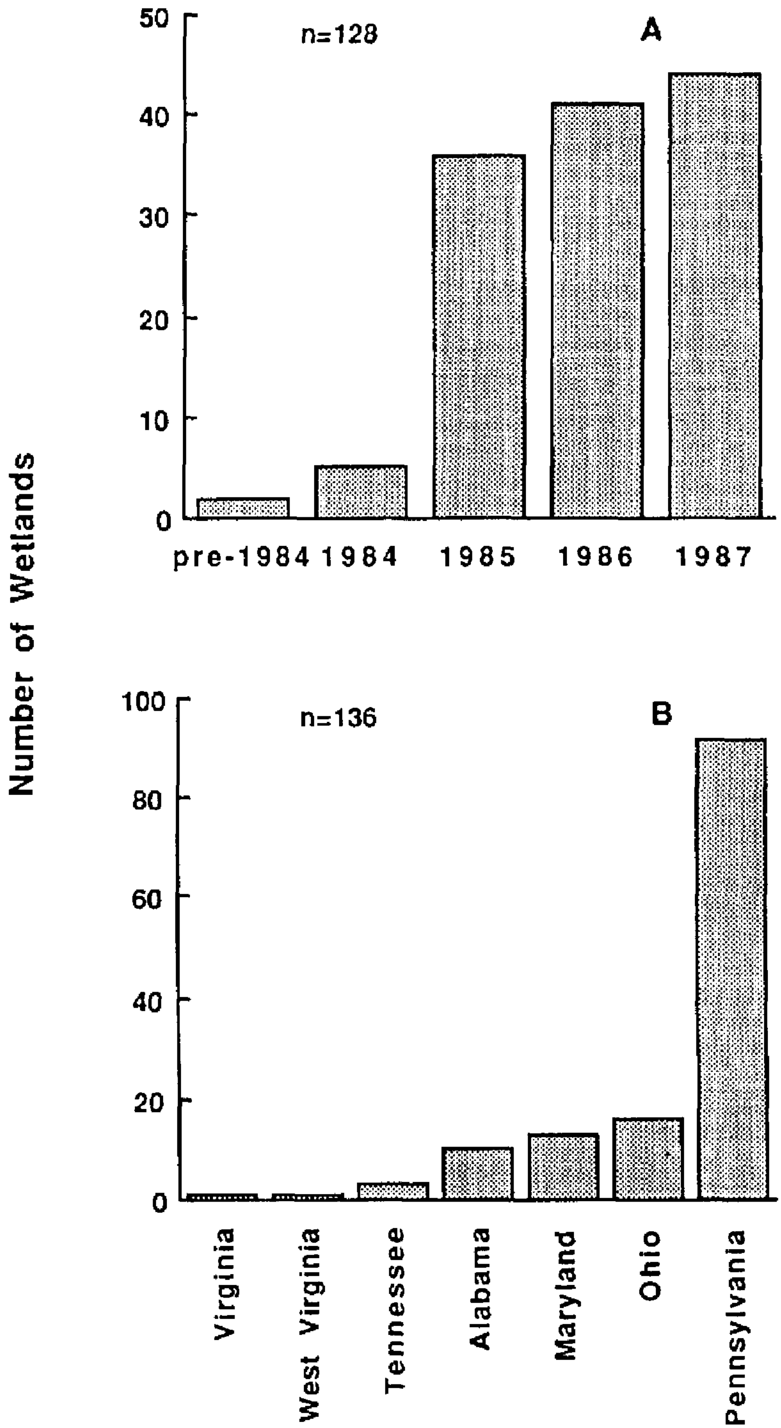

Figure 1. The number of man-made wetlands constructed to treat AMD as of spring 1988, by year (A) and by state (B).

the earliest conferences on constructed wetlands for mine drainage treatment were held in 1984 and 1985 at the Pennsylvania State University (Burris *et al.* 1984, Brooks *et al.* 1985).

Most wetlands have been constructed to treat fairly low flows of AMD; 80% of the sites have been constructed to treat flows of 100 L/min or less (Figure 2A). However, accurate measurement of either inflows or outflows is unusual. Of the 113 sites that provided unequivocal information about the method of measuring flow, 56% used simple visual estimation, 22% used occasional measurement with a bucket or flowmeter, and 16% used a single measurement with a bucket or flowmeter. At only 6% of the sites was information based on continuous measurement of flow.

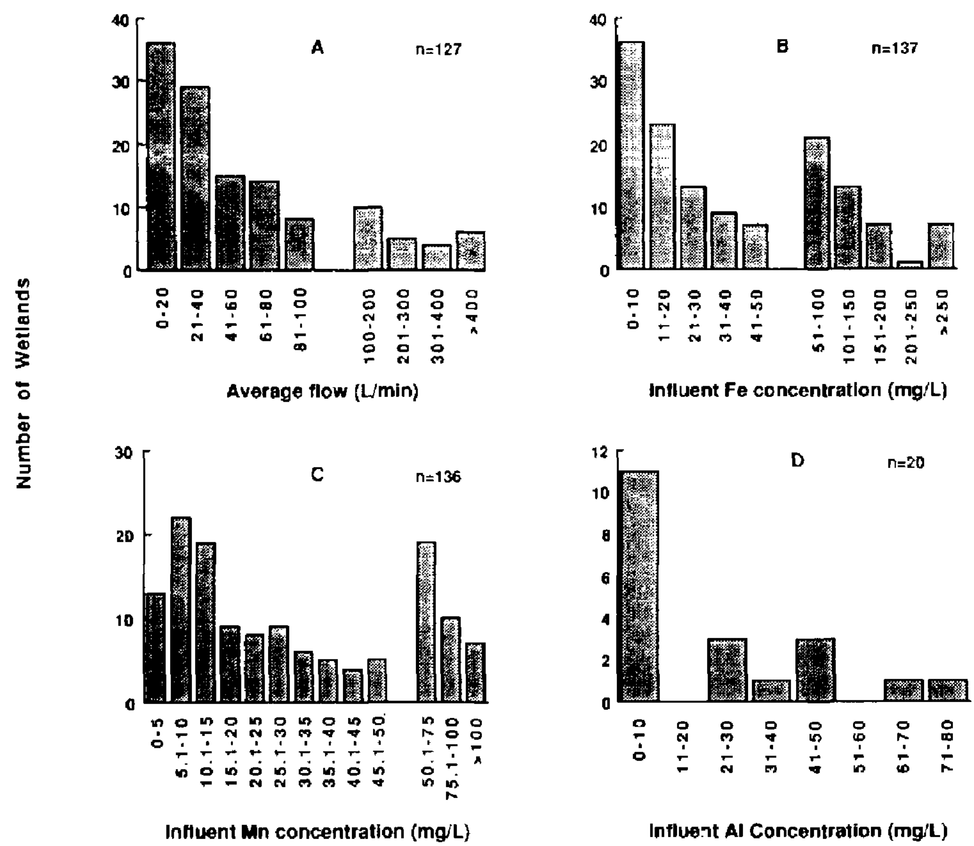

Figure 2. The number of man-made wetlands constructed to treat AMD with different flows (A) and with different influent concentrations of Fe (B), Mn (C), and Al (D).

Most wetlands have been constructed to treat AMD with fairly moderate metal concentrations; 66% of the wetlands have been constructed to treat AMD with Fe concentrations ≤50 mg/L, and 74% of the sites have been constructed to treat AMD with Mn concentrations ≤50 mg/L (Figures 2B and 2C). Although the number of sites reporting Al concentration data is small, 55% of the constructed wetlands have been constructed to treat AMD with Al concentrations ≤10 mg/L (Figure 2D). In contrast to the tendency toward constructing wetlands to treat AMD with moderate metal concentrations, more even distributions were obtained for frequencies of constructed wetlands with respect to pH and sulfate concentrations of the influent AMD (Figure 3A and 3B, respectively). About 62% of the sites had influent acidities >50 mg/L $CaCO_3$, and 39% of the sites had influent alkalinities ≤10 mg/L $CaCO_3$ (Figures 3C and 3D, respectively).

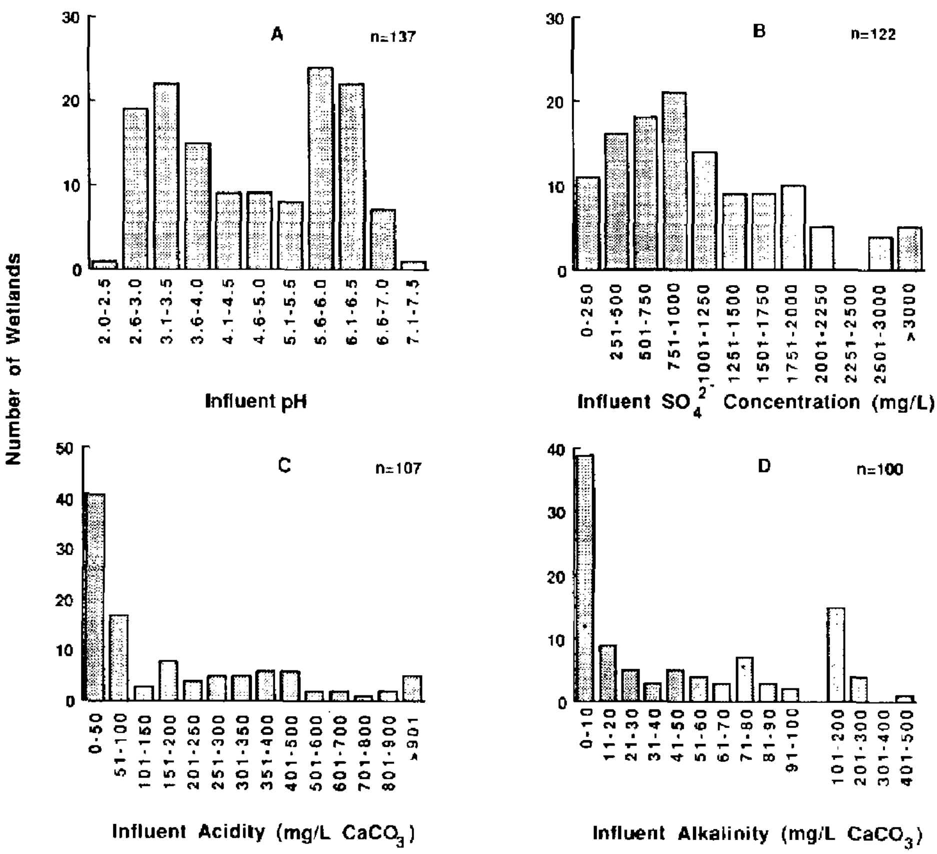

Figure 3. The number of man-made wetlands constructed to treat AMD with different influent pH values (A) and with different influent concentrations of SO_4^{2-} (B), acidity (C), and alkalinity (D).

A variety of approaches toward wetland construction has been utilized. Usually, an organic substrate is laid down, wetland vegetation is planted, and sometimes lime, limestone, and/or fertilizer is applied. The sizes of wetlands constructed for AMD treatment averaged 1417 ± 285 m^2 (mean $\pm$ standard error; n=109) and ranged from 29 to 25,000 m^2. The average depth of the organic matter in the constructed wetlands was 52 ± 6 cm (n=60). Frequently, wetland treatment systems are constructed as a series of small wetlands, commonly referred to as cells, connected by drainageways. The average number of cells per wetland treatment system was 2.6 ± 0.1 (n=137), with 35% of the systems consisting of a single cell, 21% of two cells, 21% of three cells, and the remainder with as many as 9 cells.

Organic substrates that have been used in the construction of wetland treatment systems include spent mushroom compost (27 sites), composted animal manure (20 sites), composted animal manure mixed with either hay or straw (19 sites), a mixture of animal manure and spent mushroom compost (12 sites), hay or straw only (9 sites), *Sphagnum* peat (5 sites), or a mixture of *Sphagnum* peat and hay (3 sites). In 17 of the sites, no organic material was used; wetland vegetation was planted in impoundments made from depressions in the local mineral soil and/or coal spoil.

Of the 139 constructed wetlands where vegetation was planted, either through rhizome transplants or seeding, 91% were planted with cattails (typically *Typha latifolia* or *T. angustifolia*). Occasionally, mosses (usually *Sphagnum* spp.; 16% of the sites), sedges and rushes (14% of the sites), or algae (10% of the sites) were added to the constructed wetland.

Lime, limestone, and/or fertilizer was added to 98 of the constructed wetland sites, usually for the purposes of pH modification and enhancing the establishment and growth of wetland vegetation. These additions were made either as a surface application, by incorporation into the organic substrate, or in several cases, a layer of limestone, typically 15-30 cm thick, was placed beneath the organic material. At 67 sites, lime or limestone was added to the constructed wetland, at 13 sites fertilizer was added, at 18 sites both lime (or limestone) and fertilizer were added, and at 16 sites neither lime, limestone, nor fertilizer was added.

EFFECTIVENESS OF CONSTRUCTED WETLANDS FOR AMD TREATMENT

Although the biotic and abiotic processes that contribute to the improvement of the water quality of AMD as it passes through a wetland system have been identified (cf. Wieder 1988, Fennessy and Mitsch 1989, Henrot and Wieder 1990, as well as papers in U.S. Bureau of Mines 1988), quantitative studies leading to an ability to make *a priori* predictions about the effectiveness of a wetland constructed in a particular manner to treat a given flow and chemistry of AMD are lacking.

Statistical analysis of the data obtained from the survey was undertaken to identify key design criteria that may have a substantial effect on the effectiveness of constructed wetlands for AMD treatment.

Constructed wetlands, by themselves, typically do not produce acceptable water quality; additional chemical treatment of the water discharged from the wetland is often required. Of the 137 wetland sites for which unequivocal information on the availability and use of chemical treatment was available, 61 had some sort of chemical treatment operating in addition to the constructed wetland, and 31 had chemical treatment available, but not in use. The remaining 45 sites had no chemical treatment capability in addition to the constructed wetland, suggesting that either the wetland by itself produced acceptable water quality (true for only 15 of the sites), or water with unacceptable water quality was being discharged from an active mine site, or the wetland was constructed on an abandoned mine site and therefore SMCRA and the attendant water quality regulations were not applicable.

Clearly one factor that influences the quality of the water discharged from a constructed wetland treatment system is the quality of the influent AMD. For all 7 chemical parameters about which data were collected, highly significant correlations between inflow and outflow concentrations were obtained (Table 1).

To address effectiveness in a quantitative manner for any particular chemical parameter, the change in concentration between influent and effluent water, expressed as a percentage of the influent concentration, has been used (Girts and Kleinmann 1986):

$$\text{Treatment efficiency} = \frac{\text{Inflow concentration - Outflow concentration}}{\text{Inflow concentration}} \times 100.$$

Positive values for treatment efficiency indicate that the concentration of a particular chemical parameter decreased upon passage of the AMD through a wetland, while negative values for treatment efficiency indicate that the concentration of a particular chemical parameter increased upon passage of the AMD through a wetland. In interpreting data expressed as treatment efficiencies, it must be recognized that factors other than retention or release of a particular chemical parameter can cause changes in the calculated treatment efficiency. For example, dilution of AMD by seepage into the wetland of an unknown water source with relatively good water quality could result in a lower effluent than influent concentration, and conversely evaporation of wetland water could result in a higher effluent than influent concentration (Wieder 1988). Another problem with using treatment efficiency is that a wetland that reduces the concentration of a particular chemical parameter from an influent value of 400 mg/L to an effluent value of 300 mg/L has the same treatment efficiency as a wetland that reduces an influent concentration of 40 mg/L to an

Table 1. Mean concentrations (± standard errors) of chemical parameters in AMD entering (inflow) and exiting (outflow) man-made wetlands constructed for AMD treatment, and Pearson product moment correlations between the inflow and outflow concentrations. An asterisk indicates that the correlation is significant ($p \leq 0.05$). Values in parentheses represent sample sizes.

Chemical parameter	Inflow Concentration	Outflow Concentration	Pearson Product Moment Correlation
H^+ (ueq/L)	306.1 ± 44.5	188.9 ± 36.6	0.60*
pH	3.51	3.72	
	(137)	(128)	(125)
Acidity (mg/L $CaCO_3$)	257.1 ± 39.9	125.9 ± 30.6	0.86*
	(107)	(99)	(94)
Alkalinity (mg/L $CaCO_3$)	55.6 ± 7.5	96.8 ± 14.7	0.31*
	(101)	(92)	(88)
Total Fe (mg/L)	60.6 ± 6.8	15.4 ± 3.2	0.63*
	(137)	(129)	(126)
Total Mn (mg/L)	37.7 ± 3.5	24.0 ± 3.0	0.86*
	(136)	(127)	(124)
Total Al (mg/L)	21.2 ± 5.7	10.8 ± 3.0	0.72*
	(20)	(21)	(20)
SO_4^{2-} (mg/L)	1194 ± 93	997 ± 82	0.84*
	(122)	(109)	(106)

effluent concentration of 30 mg/L. A much better indicator of wetland performance would be the total quantity of a particular chemical constituent removed by a wetland per area per time. However, calculation of this type of performance requires accurate measurement of hydrologic fluxes into and out of a given wetland system and unfortunately such hydrologic data are rarely available. Being aware of these caveats, and in the absence of good hydrologic data, treatment efficiency is used in this paper as a measure of retention or release in a constructed wetland system.

Mean treatment efficiency values (Table 2) indicated that constructed wetlands decreased acidity, total Fe, total Mn, and total Al concentrations and increased H^+ concentrations, while sulfate concentrations remained essentially unchanged. However, treatment efficiency was not normally distributed for several chemical parameters (Figure 4). A more meaningful interpretation is afforded by identification of quantiles for the 6 distributions depicted in Figure 4. For example, although mean treatment efficiency for H^+ was -311%, outstanding treatment efficiencies (greater than 98.2%) were obtained at 25% of the sites (difference between the 100th and 75th quantile), and treatment efficiencies greater than 68.4% were obtained at half of the sites (Table 2).

Table 2. Summary statistics for treatment efficiencies. For each chemical constituent of AMD, the tabular value in the 100% quantile column represents the maximum treatment efficiency and the tabular value in the 0% quantile column represents the minimum treatment efficiency. The intermediate quantiles denote the treatment efficiency below which a certain percentage of all observations fell. Also provided is the arithmetic mean and standard error for the treatment efficiency for each chemical parameter; n represents the number of observations.

Chemical constituent of AMD:	Treatment efficiencies for a quantile of: 100	75	50	25	0	Quantile for zero treatment efficiency	Mean ± SE	n
H^+	100.0	98.2	68.4	0.0	-15749	29	-311 ± 167	125
Acidity	100.0	100.0	66.8	32.8	-200.0	11	56.6 ± 6.1	74
Fe	99.9	93.8	80.9	46.6	-567.0	13	58.2 ± 6.5	126
Al	90.9	78.9	47.7	5.6	-52.9	25	39.0 ± 10.0	20
Mn	99.9	64.1	34.1	9.4	-1100	17	16.8 ± 13.0	124
SO_4^{2-}	88.6	25.6	8.1	-3.5	-812.0	38	0.6 ± 8.5	106

Two quantities in Table 2 are probably most useful in terms of assessing wetland performance: the treatment efficiency that represents the 50th quantile and the quantile that corresponds to 0% treatment efficiency. The former value provides an indication of the magnitude of treatment efficiency that could be anticipated with a 50% probability (the 75th and 25 quantiles provide analogous interpretations).

The latter value corresponds to the probability that a wetland will have negative treatment efficiency, i.e., effluent concentrations will be greater than influent concentrations. Thus, the survey data indicate that when using a constructed wetland for Fe removal, there is a 50% probability that a treatment efficiency of 80.9% or better would result, but there is also a 13% probability that the wetland will exhibit net release rather than net retention of Fe.

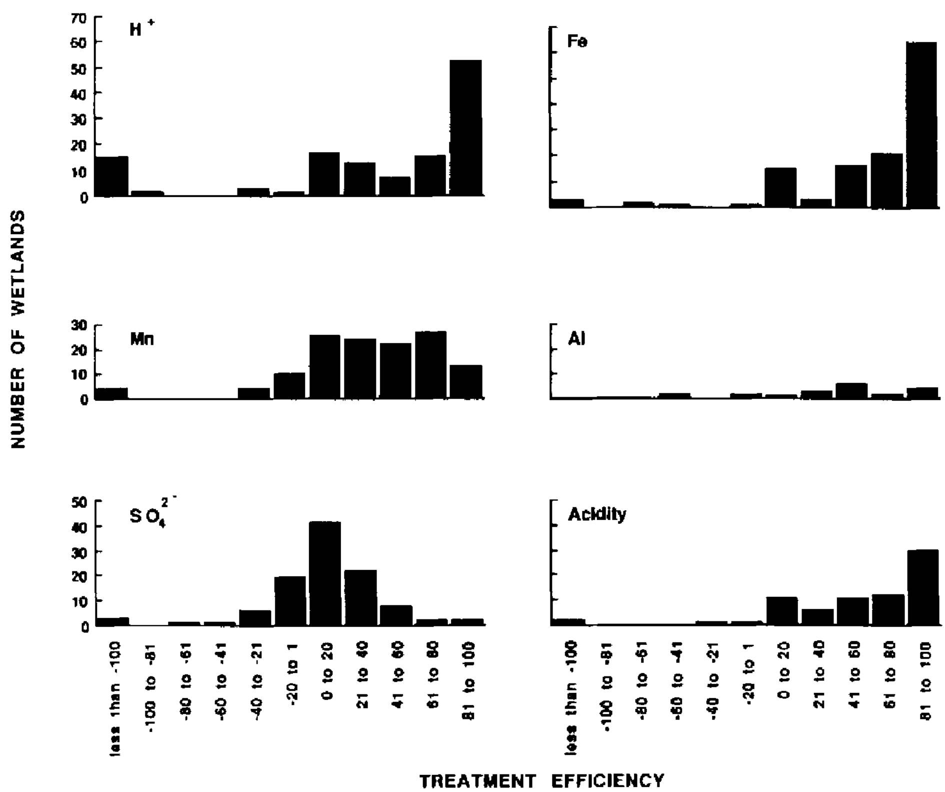

Figure 4. Frequency distributions of treatment efficiencies (defined in text) for 6 chemical characteristics of AMD. Quantiles further describing these distributions are given in Table 2.

To assess what design parameters might have a significant effect on wetland performance, simple correlations between treatment efficiencies and design parameters were performed (Table 3). Of the 54 correlations in Table 3, only 9 were significant. Increasing the area of a constructed wetland was positively correlated with enhanced treatment efficiency for Fe but not for any other chemical constituent of AMD. In contrast, increasing the depth of the organic matter substrate in a constructed wetland was associated with decreased treatment efficiencies for both Fe and Mn. Surprisingly, increasing the input of Fe to a constructed wetland, whether

Table 3. Spearman rank correlations between potential design parameters and treatment efficiencies. An asterisk denotes a significant correlation ($p \leq 0.05$). Values in parentheses represent sample sizes.

	Treatment efficiency for:					
Design parameter	H^+	Acidity	Fe	Mn	Al	SO_4^{2-}
Wetland area (m^2)	-0.12 (99)	0.06 (63)	0.23* (100)	0.04 (98)	0.01 (19)	0.02 (82)
Wetland depth (cm)	-0.24 (57)	-0.22 (38)	-0.29* (58)	-0.37* (57)	-0.05 (17)	0.01 (50)
Wetland volume (m^3)	-0.08 (49)	0.01 (34)	-0.11 (50)	-0.28 (49)	-0.11 (16)	-0.01 (42)
Number of cells	-0.17 (123)	-0.03 (73)	0.06 (124)	-0.07 (122)	-0.19 (20)	-0.02 (105)
Inflow rate (L/min)	-0.09 (102)	0.14 (73)	0.07 (103)	-0.14 (101)	-0.06 (19)	-0.03 (93)
Inflow rate/area (L/min/m^2)	-0.03 (86)	-0.11 (63)	-0.09 (87)	-0.08 (85)	-0.02 (18)	0.002 (79)
Inflow concentration for a particular element (meq or mg/L)	0.11 (125)	-0.22 (74)	0.39* (126)	0.07 (124)	0.11 (20)	0.32* (106)
Flux to wetland for a particular element (mg/min)	0.10 (102)	-0.26* (63)	0.39* (103)	0.02 (101)	0.01 (19)	0.13 (93)
Flux/area to wetland for a particular element (mg/min/m^2)	-0.04 (85)	-0.27* (63)	0.27* (87)	-0.01 (35)	0.12 (18)	0.10 (79)

expressed as concentration in the influent AMD (mg/L), flux of Fe to the wetland (mg/min), or flux of Fe per area of wetland (mg/min/m^2), resulted in enhanced Fe treatment efficiency. Similarly, greater SO_4^{2-} treatment efficiency was associated with higher SO_4^{2} concentration in the influent AMD, although there was little evidence for retention of SO_4^{2-} in these constructed wetlands (Figure 4). In contrast, treatment efficiency for acidity was diminished by greater fluxes of acidity or greater fluxes per area of acidity entering a constructed wetland. Neither wetland volume, the number of cells in a wetland, the inflow rate of the AMD entering the wetland, nor the flow rate per wetland area were significantly correlated with treatment efficiency for any of the chemical constituents of AMD. Treatment efficiencies for H^+ and Al were not significantly correlated with any potential design parameter.

The results from the correlation analyses do not support the commonly held and intuitively reasonable assumption that the larger the constructed wetland, the greater the treatment efficiency, and thus the higher the probability of successful treatment of the AMD. Moreover, in general, neither lower flow rates, lower concentrations of chemical parameters, lower loadings, nor lower loadings per area of wetland produced markedly improved (i.e., was significantly positively correlated with) treatment efficiencies. The overall absence of significant correlations between any of the design criteria and any of the measures of treatment effectiveness brings into question the usefulness of the only published recommendations for sizing wetlands according to flow of the AMD and chemistry of the AMD to be treated (Kleinmann *et al.* 1986, Brodie *et al.* 1988).

Although the correlation analysis did not identify specific design criteria for improving AMD treatment with constructed wetlands, it is conceivable that two additional aspects of wetland construction, chemical amendments and choice of organic material, might be important in predicting effectiveness. To address this possibility, Kruskal-Wallis tests were carried out with each of the 6 treatment efficiencies in Table 3 as dependent variables and with the main effect of either chemical amendment (lime/limestone, fertilizer, both, neither) or organic material (spent mushroom compost, composted animal manure, hay/straw, *Sphagnum* peat, a mixture of composted animal manure with hay/straw, a mixture of composted animal manure and spent mushroom compost; a mixture of *Sphagnum* peat with hay/straw, or no organic material used in construction of the wetland).

The type of chemical amendment had no effect on treatment efficiency for any of the AMD chemical constituents (chemical constituent and associated P value: H^+, 0.71; acidity, 0.98; Fe, 0.17; Al, 0.38; Mn, 0.68; SO_4^{2-}, 0.20). Similarly, with the exception of Fe, the type of organic substrate used had no effect on treatment efficiency for the chemical constituents of AMD (chemical constituent and associated P value: H^+, 0.13; acidity, 0.20; Fe, 0.04; Al, 0.45; Mn, 0.18; SO_4^{2}, 0.53). Although organic substrate type did affect Fe treatment efficiency, the only organic substrate with a significantly lower Fe treatment efficiency was a mixture of *Sphagnum* peat and hay/straw. This type of organic substrate was used in only 3 constructed wetland systems (Table 4).

Table 4. Multiple comparisons following a significant effect of the type of organic substrate used in a man-made wetland (Kruskal-Wallis test, $p = 0.04$) with regard to Fe treatment efficiency. Mean rank values with the same letter superscript do not differ significantly ($p = 0.05$).

	Fe treatment efficiency			
Type of organic substrate	Mean value	Median value	Mean rank	n
Manure with mushroom compost	84.1	92.2	81.5[a]	12
No organic matter added	75.7	92.2	79.9[a]	17
Hay/straw	84.5	88.3	79.3[a]	9
Mushroom compost	63.0	80.0	61.2[a]	27
Manure	59.1	72.8	58.7[a]	20
Sphagnum peat	22.2	79.6	56.8[a]	5
Manure with hay/straw	61.8	57.9	53.8[a,b]	19
Sphagnum peat with hay/straw	-164.6	0.0	22.0[b]	3

IMPLICATIONS AND CONCLUSIONS

The OSMRE survey was conducted with the hope that by collecting and synthesizing information from all known wetlands that had been constructed for the treatment of AMD, any consistent overall trends would emerge. More specifically, it was anticipated that data from the survey could help formulate design criteria to reliably predict treatment effectiveness, given a particular volume and chemistry of AMD. Even if the survey itself did not generate considerable improvement in predictive capability, it was hoped that the survey would identify key parameters for further research on maximizing constructed wetland treatment system efficiency.

The data collected from the survey indicate that, on average, concentrations of some AMD chemical constituents (notably acidity, Fe, Al, and to a lesser extent Mn) are reduced by various degrees as a result of passage through a constructed wetland (Tables 1 and 2). However, in general, water quality improvement was not strongly related to either AMD chemistry or intuitively sensible design parameters (Table 3). The survey and subsequent synthesis has not substantially enhanced the ability to make *a priori* predictions about the effectiveness of a constructed wetland treatment system, given a particular flow and chemistry of AMD.

Only rarely (in 15 of the 137 constructed wetland sites in the survey) has a constructed wetland sufficiently modified the AMD chemistry so that the discharge from the wetland met specified water quality criteria. From a regulatory perspective, if a constructed wetland system fails to achieve acceptable water quality, then conventional chemical treatment must be initiated, at an expense additional to that of wetland construction. Without reliable predictive ability, attempts at cost-benefit analyses for contemplated constructed wetlands for AMD treatment must be fraught with unacceptable uncertainty (Wieder *et al.* 1989). The information obtained from the survey, when considered in conjunction with previously published studies, suggests that the effectiveness of wetland treatment of AMD is not only extremely variable, but also presently not predictable. At this point in time, it remains questionable that constructed wetland systems may represent a low-cost, low maintenance alternative to chemical treatment of AMD (Wieder and Lang 1982, Kleinmann *et al.* 1983).

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