THE BARK CAMP RUN DEMONSTRATION CONSTRUCTED WETLANDS: FINDINGS AND RECOMMENDATIONS FOR FUTURE DESIGN CRITERIA

by

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Abstract The performance of six wetlands built to ameliorate acid mine drainage has been analyzed over 806 days. The wetlands are each 52 m x 8 m at the water surface, with a 5 cm surface water column and 60 cm depth of substrate consisting of horse manure mixed with an equal volume of SiO_2 stone. Each wetland has a 1 mm polyethylene liner and wooden deflectors every 2 m to promote uniform flow. The dominant macrophyte is *Typha latifolia*. Flows are ~10 m^3/d. Median influent pH = 3.0; acidity = 202 mg/L as $CaCO_3$; [Fe^{+3}] = 22.9 mg/L; [Fe^{+2}] = 0.8 mg/L; [Al] = 10.9 mg/L; [Mn] = 2.0 mg/L; and [SO_4^{-2}] = 592 mg/L. Water quality was determined biweekly for each wetland's influent and final effluent and at 84 internal sampling stations built to sample at depths 5, 25, 45, and 60 cm below the water surface. Tracer studies showed that the mine drainage flows through both the surface water column and the substrate, and a one-dimensional flow model appears satisfactorily to explain the performance of the wetlands. Wetlands should be designed to achieve uniform flow and to maintain flow through the substrate A polishing area of a few m^2 with a substrate consisting only of limestone chips appears to be helpful in maintaining effluent alkalinity. Simple mathematical models were developed to assess the performance of the constructed wetlands. Removal of Fe^{+3} is by hydrolysis, followed by reduction to Fe^{+2} and incorporation into the substrate. Removal of Al^{+3} is by hydrolysis. The observed removal rates of 1g d^{-1} m^{-2} for Fe^{+3} and 0.5g d^{-1} m^{-2} for Al^{+3}, combine with concurrent neutralization of the resulting H^+, to give an acidity removal rate of 5.5g d^{-1} m^{-2}. A zero-order rate law can be used to describe the observed rate of Fe^{+3} removal First-order rate laws also produce good representations for the rates of Fe^{+3} and Al^{+3} removal. Effluent Mn concentration > influent [Mn], and declines in accordance with a first-order rate law, indicative of desorption of Mn^{+2} initially present in the substrate. This may explain past difficulties in assessing Mn removal in anaerobic constructed wetlands.

Additional Key Words: water pollution abatement, constructed wetlands design, mathematical modeling.

Introduction

The PA Department of Environmental Protection (DEP 1988) has reported that discharges from coal and clay mining operations account for pollution of approximately 2700 km of Pennsylvania's streams. At least 794 discharges are being treated by current coal operators to conform to effluent limits (Hellier, *et al.* 1994). A large number of discharges are from operations that were abandoned before current mining laws were passed; for example, the Muddy Run watershed receives 15.75 metric tons of acid per

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day from abandoned mines (Skelly and Loy 1972). To restore the quality of the polluted streams, a technologically feasible and cost-effective means must be found to abate the pollution from these discharges.

The United States Environmental Protection Agency (EPA 1982) has approved chemical treatment for mine discharges; however, because of the cost, passive treatment methods, including constructed wetlands, are also being used to treat mine discharges of different qualities. While there have been several studies and reports on the subject of constructed wetlands, and design guidance manuals have been published (Hedin *et al.* 1994), there is little theoretical discussion on the basis for the design of constructed wetlands.

Objectives

The objectives of this study were: (1.) To study the performance of wetlands built to take advantage of anaerobic processes in treating a mine discharge with moderate acidity and moderately elevated metals; (2.) To obtain transient and long term water quality data at key sample points in the wetlands.; (3.) To determine flow patterns within the wetlands; (4.) To assess the effects of moderate pretreatment of the wetland influents with anhydrous NH_3; (5.) To develop simple mathematical models from the data obtained, upon which future designs can be based; and (6.) To compare the design criteria produced by the mathematical models to previous design criteria, and to compare the performance of the demonstration wetlands to the performance of existing wetlands.

Site Selection

The site of the abandoned Bark Camp #1 and #2 deep mines and coal processing facility was selected for the study because: (1.) The discharge had a moderate acidity of < 300 mg/L as $CaCO_3$ and a moderate Fe concentration of < 30 mg/L, indicating a reasonable likelihood of successful treatment and that there was a reasonable chance to improve the quality of the degraded stream; (2.) The landowner, the Pennsylvania Bureau of Forestry, approved of the project and provided assistance; and (3.) It was within reasonable travel time of the office.

Bark Camp Run is located in Huston Township, Clearfield County, PA, and has been impacted by the abandoned mining operation. as shown by the following results obtained 9/4/90, before the study was initiated: pH = 5.5; acidity = 22 mg/L as $CaCO_3$ (alkalinity = 3 mg/L); $[Fe^{+3}]$ = 7.1 mg/L; [Al] =2.7 mg/L; [Mn] = 0.9 mg/L; $[SO_4^{-2}]$ = 186 mg/L; no fish are present.

Upstream of the study area, the respective parameters were: pH = 6.9; acidity = 0 mg/L as $CaCO_3$ (alkalinity = 18 mg/L); $[Fe^{+3}]$ = 0.2 mg/L; [Al] = 0.2 mg/L; [Mn] = 0.1 mg/L; $[SO_4^{-2}]$ = 161 mg/L, and around 50 trout/km were found. Bennetts Branch Sinnemahoning Creek, to which Bark Camp Run is tributary, is stocked with trout by the PA Fish and Boat Commission.

The Bark Camp Run watershed area is 726 ha, and the stream flow is on the order of 7000 m^3/day downstream of the study area. The combined mine discharges from the study area contribute nearly 700 m^3/day of this flow. During the study, the following median values were found for the discharge: pH = 3.0; acidity = 202 mg/L as $CaCO_3$; $[Fe^{+3}]$ = .22.9 mg/L; $[Fe^{+2}]$ = 0.8 mg/L; [Al] = 10.9 mg/L; [Mn] = 2.0 mg/L; and $[SO_4^{-2}]$ = 592 mg/L.

Constructed Wetlands Design

Six constructed wetlands were built, each with a 1mm polyethylene liner on the bottom and 2 (horizontal) :1 (vertical) in-slopes to prevent groundwater exchange. The wetlands were 52 m long and 8 m wide at the water surface. The design freeboard is 35 cm, surface water column depth 5 cm, and substrate depth 60 cm. The top 5 cm of substrate is topsoil, and the remaining 55 cm is a mixture that is 50% by volume horse manure and 50% by volume river gravel with approximately 5 cm dimension and composed primarily of SiO_2. This rock, rather than limestone, was added to the substrate in order to assess the effects of allowing all the alkalinity to be generated through dissolution from the substrate and by biological reactions, without supplementation of the substrate with limestone. The manure itself had been freshly generated over the past winter and had a measured alkalinity of approximately 15000 mg $CaCO_3$ equivalent per kg dry weight. The substrate in the initial 2m length at the influent barrel consisted of the aforesaid stone alone, while the substrate in the last 2m immediately preceding the effluent barrel consistent of crushed limestone of about 1.5 cm dimension.

From three manhole/mixing chambers, influent was directed into pairs of wetlands via a barrel around whose bottom 15 cm periphery were drilled 6 mm holes. The effluent barrels were of the same design. Wooden deflectors were built every 2m along the wetlands' length to promote uniform flow. Sample stations were built to measure water quality at depths of 5 cm, 25 cm, 45 cm, and 60 cm after 128 m^2, 256 m^2, and 384 m^2 of wetland area for all six wetlands; also after 96 m^2 for wetland #2 and after 48 m^2 for wetlands #4 and #6. The dominant macrophyte was *Typha latifolia*. Figure 1 is a plan view of the wetlands. The areas given are the cumulative wetland areas from the inlet to the sample stations depicted.

Anhydrous ammonia was used for a one year period to adjust influent pH. Mixing chamber pH was adjusted in an effort to deliver an influent having pH = 3.0 to wetlands #1 and #2; pH = 4.0 to wetlands #3 and #4; and pH = 5.0 to wetlands #5 and #6.

Methods

Biweekly water quality samples were obtained upstream and downstream of the study area and from the final treatment basin, at the wetland influent and effluent, and at the 12 internal sample points of the odd numbered wetlands and 16 internal sample stations of the even numbered wetlands. Each sample was separated into two aliquots to facilitate laboratory processing; one aliquot to be analyzed for pH , alkalinity, acidity, and $[SO_4^{-2}]$ and the other to be analyzed for $[Fe^{+2}]$, total [Fe], [Mn], [Mg], and [Al]. The latter aliquot was acidified to pH < 2.0. Additionally, the effluents were analyzed for Cl^-, P, K, BOD, and forms of N. The samples were put into iced containers and transported to the Department's laboratory in Harrisburg, where they were analyzed following EPA approved methods (APHA 1992).

Influent flows were measured with a beaker and stop watch on most occasions when the water quality samples were taken. When influent flow rates were not measured, they were estimated by interpolation between measured values. Because influent flows remained very steady from measurement to measurement, the instantaneous measurement was considered to be representative. Effluent flow rates, while measured, proved less representative because they were more sensitive to daily evaporation and rainfall.

A tracer study was conducted to determine flow patterns in the wetlands (Donahue 1994). On June 9, 1993, 11.6 kg of NaBr was dissolved in water and poured into the influent barrels of wetlands #1 and #2 during one half hour. Over 68 days, samples from all of the two wetlands' sample points were analyzed at the Pennsylvania State University for $[Br^-]$, and breakthrough curves of $[Br^-]$ as a function of time were developed.

Results and Discussion

The performances of the six wetlands are illustrated and discussed in the report to EPA (Hellier 1996). Flows varied over time, but usually were less than 15 m^3/day. The effluent pH was usually near 6.0, contrasted with an influent pH of 3.0. The wetlands tended to impart alkalinity as shown by an effluent which was alkaline to neutral as contrasted with an influent with a median acidity of 202

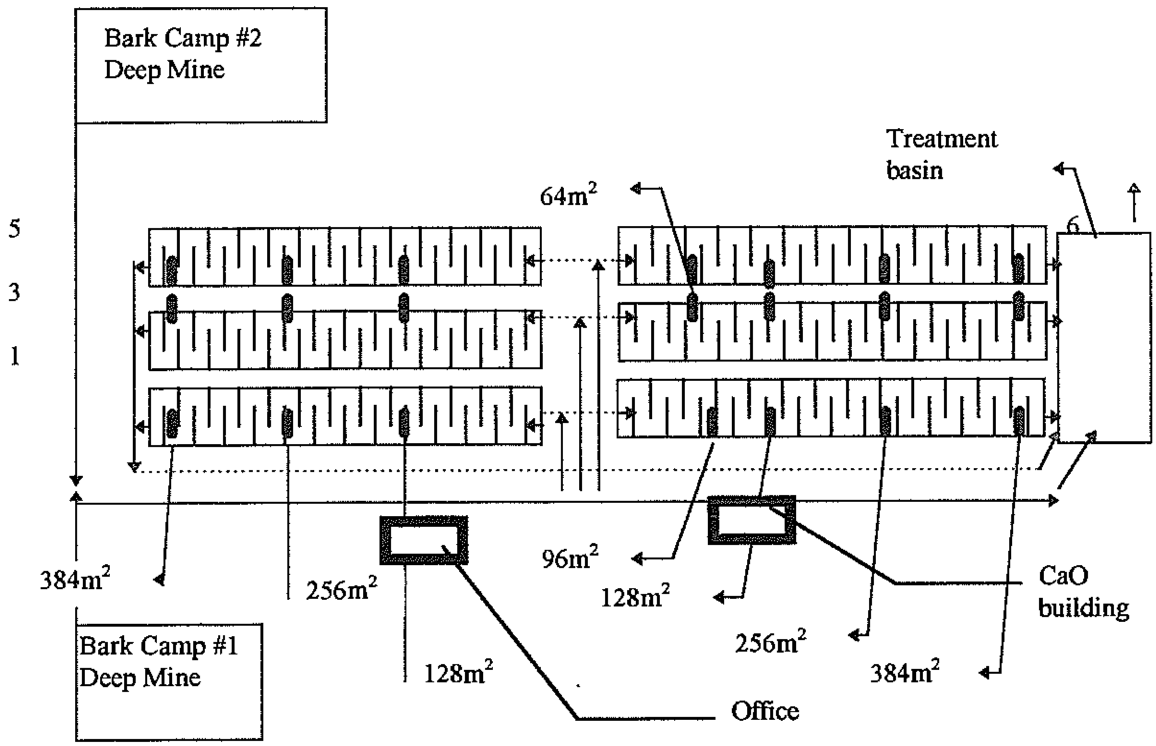

Figure 1.Plan View of Bark Camp Run Constructed Wetlands.

mg/L. Effluent [Fe^{+3}] tended to be about an order of magnitude lower than influent [Fe^{+3}], and most of the effluent Fe was Fe^{+2}. Total Fe removal was effective for the period from about 130 days to 400 days. After 400 days, Fe continued to be removed, although not as efficiently. The wetlands have been effective in removing Al, but effluent [Mn] has consistently exceeded influent [Mn]. For the purpose of illustration, the overall performance of wetland #1 is shown (Figure 2).

Graphs were made of the pollution indicators as a function of time at constant depth in the substrate for the different cumulative treatment areas, and at constant cumulative treatment area for the four different depths within the substrate. For the present discussion, Figure 3 presents the [Fe^{+3}] data for wetland #1. The results for the indicators are summarized as follows: (1) Net acidity tended to decline and pH to increase with increasing depth, although no regular pattern is apparent. Deeper parts of the substrate tended to maintain alkaline conditions better over time compared to the surface water column and the shallower parts of the substrate. (2) Total [Fe] tended to decline with depth, with [Fe^{+3}] being lowered relative to influent [Fe^{+3}] and [Fe^{+2}] being elevated; (3) [Al] tended to be lowered relative to influent concentrations, but (4) [Mn] was elevated relative to influent concentrations; (5) [SO_4^{-2}] fluctuated, and no apparent pattern was observed.

The tracer breakthrough curves at the four different depths at a cumulative treatment area of 128 m^2 are shown for wetland #1 (Figure 4). Based on the breakthrough curves, detention times were calculated. The flow characteristics of wetland #1 were assumed to apply to wetlands #3 and #5; the characteristics of wetland #2, to wetlands #4 and #6. To apply the results to a given water quality sampling period, detention time was assumed to be proportional to influent flow. Detention times behaved regularly

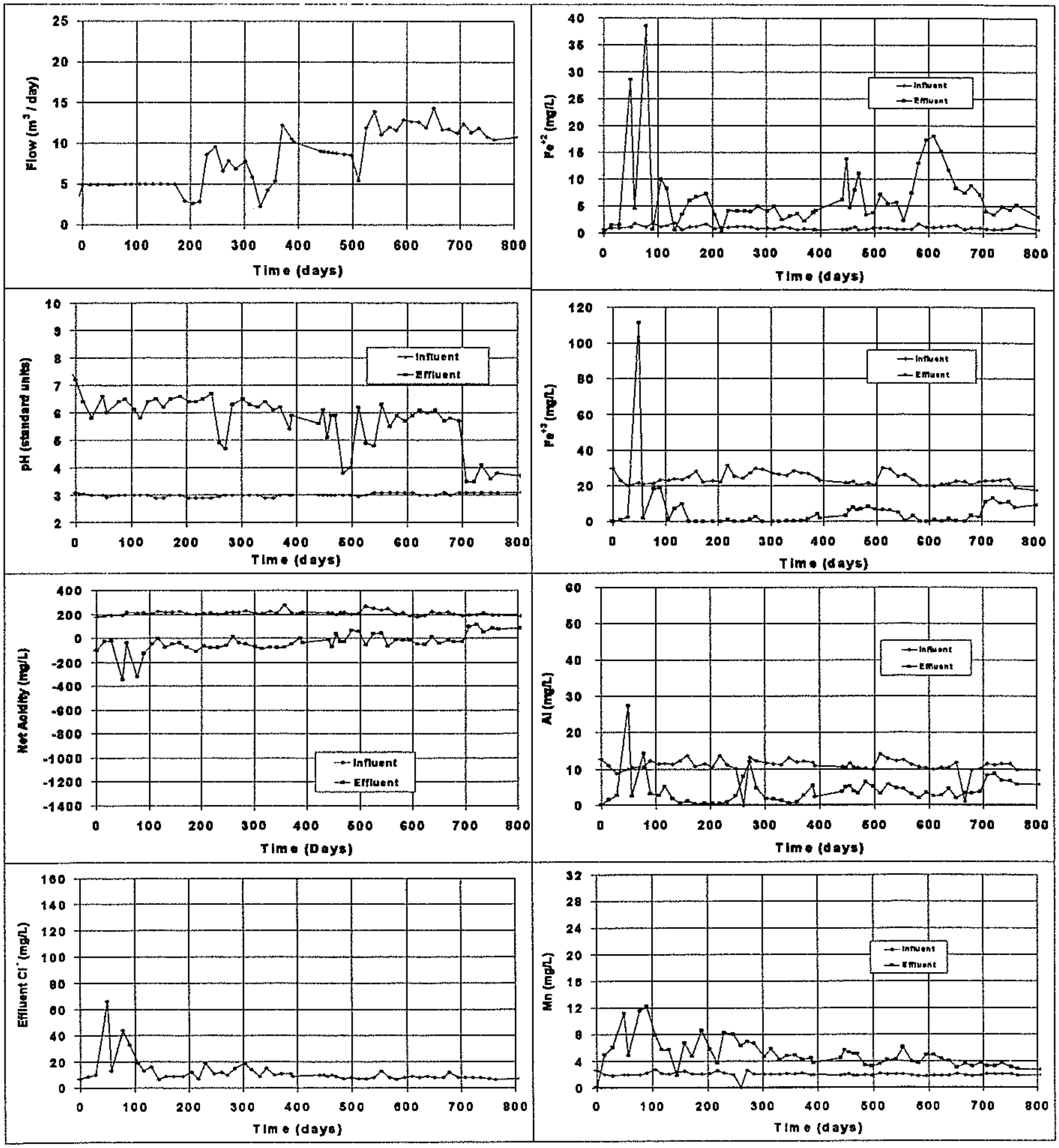

Figure 2. Overall Performance of Wetland #1.

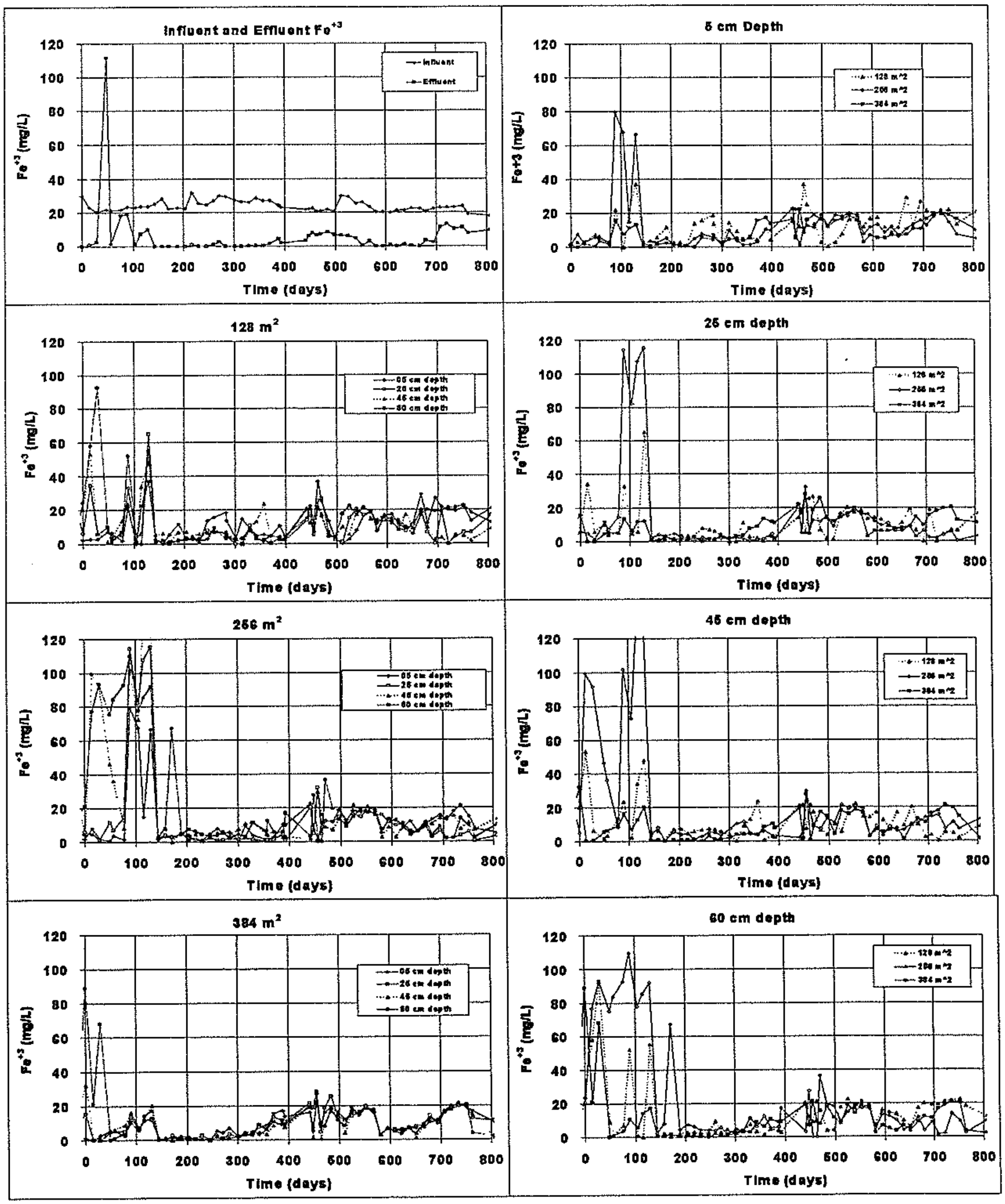

Figure 3. Wetland #1 Removal of Fe^{+3}.

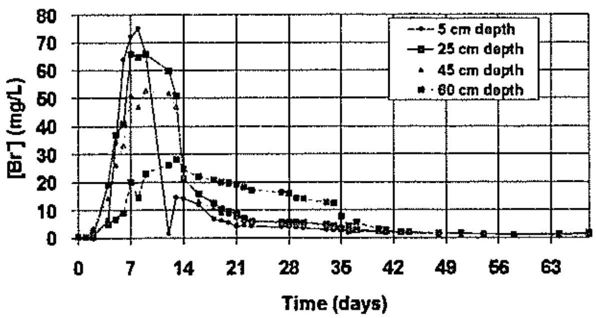

Figure 4: Wetland #1 [Br⁻] after 128 m² Area

and increased with increasing depth, suggesting the first approximation of a one-dimensional flow pattern in which flow was uniform and varied only in the vertical direction throughout most of the wetlands. The irregularities exhibited near the influent can be attributed to a drawdown effect resulting from the effluent being taken from the bottom of the effluent barrels.

The study period appears to be divided into three phases: (1.) A transient startup period in which the wetland acclimates to the mine drainage flow and reaches steady operation. During this phase, the effluent exhibits elevated [Cl^-] and [Fe], indicative of possible desorption and flushing from the substrate. The transient period is not identical for all pollutants; for example, [Mn] continues a downward trend. (2.) A steady period in which the wetlands generate alkalinity, remove acidity, and are very effective in removing Fe; (3.) A declining effectiveness period in which the wetlands begin to lose their alkalinity generation capabilities and Fe removal becomes less effective. During this period, the limestone chip polishing area appears to remove between 30% and 100% of the Fe^{+3}. The declining wetland effectiveness may be due to the loss of the alkaline material originally present in the horse manure. Both of these facts suggest that limestone, rather than inert stone (SiO_2), should be incorporated into the substrate to maintain the performance of the wetlands.

The anhydrous NH_3 addition accelerated the deposition of FeOOH at the entrance to the wetlands, as evidenced by the coloration of the substrate surface: wetlands #1 and #2 had no coloration; wetlands #3 and #4 had some coloration; and wetlands #5 and #6 had substantial coloration. Influent pH in all six wetlands returned almost instantaneously to 3.0 as the Fe^{+3} was hydrolyzed.

Mathematical models

The development of a comprehensive mathematical model to explain the behavior of all pollutant indicators is beyond the scope of this report. Model development will be illustrated by considering the removal of Fe in the first 128 m^2 of treatment area during the steady phase of the study.

The 22.90 mg/L median influent [Fe^{+3}] accounts for 96% of the influent Fe. Mechanisms of Fe^{+3} removal from the water include (1) Hydrolysis of Fe^{+3} followed by precipitation as FeOOH from the surface water column and retention as a solid on the surface of the substrate; (2) Hydrolysis of Fe^{+3} and retention of the resulting FeOOH within the substrate; (3) Reduction of Fe^{+3} to Fe^{+2} within the substrate, followed by its Fe^{+2} retention in the substrate as organically bound Fe^{+2}, FeS, or $FeCO_3$.

The following assumptions were made to develop a simple model: (1.) The transient startup period having passed, on any sample day during the steady period of operation, the influent flow and indicator concentrations are steady. (2.) Plug flow conditions apply in the surface water column and within the substrate. This assumption is justified by considering that the flow is low relative to the wetland volume, and that the deflectors and the *Typha latifolia* enhance uniform, plug flow. (3.) Flow components in the x direction (along the length of the wetland) are large relative to flow components in the y or z directions; (4.) To permit the use of differential equations, the water column and the substrate are considered mathematically to be continuous media; (5.) The rate expression for a given indicator depends only on the concentration of that indicator.

Zero order model

Historically, expressions of rate for removal of pollutants in constructed wetlands have been simple linear representation based on the mass of pollutant removed per unit area per unit time; i.e., g day^{-1} m^{-2} (US Bureau of Mines, *op. cit.)*. If the wetland depth is constant, or if an average depth is used, this representation considers the removal rate *independent* of concentration:

$$d[Fe^{+3}]/dt = -k_0 \quad (1)$$

The zero-order rate constant k_0 is given by:

$$k_0=([Fe^{+3}]_{in}-[Fe^{+3}])/(\tau-\tau_{in}) \quad (2)$$

where the subscript "in" stands for conditions at the beginning of the wetland section being considered, and τ stands for detention time as determined from the tracer breakthrough time (Figure 4) and influent flow rate. For each wetland, the rate constant k_0 was determined between sampling stations at the different depths, (Figure 3), removal rates were calculated at those depths, and the composite rate of removal in each section of the wetland was calculated by averaging among the rates at the four depths. The rate of Fe^{+3} removal, g day^{-1} m^2 is shown in Table 1. The removal rate for the first 128 m^2 of the wetlands is consistent with removal rates that DEP has observed in other wetlands receiving acidic influents. However, the calculated removal rates in this first one-third of the wetland is sensitive to the position within the wetland. This suggests, particularly for the first 128 m^2 of the wetland, that a different rate expression might be more valid. The calculated removal rates in the remainder of the wetland are less consistent, and may indicate a change in mechanism to which a different model must be applied.

First-order model

The use of a first-order rate law to describe pollutant removal is common practice in sanitary engineering. The first order rate expression:

$$d[Fe^{+3}]/dt = -k_1[Fe^{+3}] \quad (3)$$

can be combined with the simplifying assumptions given above to calculate the first-order rate constant k_1:

$$k_1=\ln([Fe^{+3}]_{in}/[Fe^{+3}]_{out})/(\tau-\tau_{in}) \quad (4)$$

The procedure for calculating removal rates in g day^{-1} m^{-2} was similar to that used for the zero-order model. The removal rates are given in Table 2. They are again sensitive to the position in the wetland. The tendency of the removal rate to decline as the position of a particular treatment area of the wetland becomes further removed from the influent suggests that the removal rate does depend on $[Fe^{+3}]$ and lends credence to a first or higher order model.

The removal of Al was also considered, using a first-order rate expression, (Table 3). The behavior of [Mn] (Fig. 2) indicates that desorption from the substrate is occurring, possibly in accordance with a first-order rate law.

Conclusions

The procedures outlined above give a reasonable, simple predictive tool for the design of constructed wetlands. If a conservative figure of 1.0 g day^{-1} m^{-2} removal rate is taken for Fe^{+3} and the similarly derived 0.5 g day^{-1} m^{-2} removal rate is taken for Al^{+3}, and both removals are converted into acidity equivalents:

$$\text{Acidity equivalent} = 2.6883\ Fe^{+3}] + 5.5643\ [Al^{+3}] \quad (5)$$

an acidity removal rate of 5.5 g day^{-1} m^{-2} as $CaCO_3$ equivalent is calculated for the Bark Camp Run wetlands. This agrees well with the US Bureau of Mines (Hedin *et al.* 1994) guideline of 5.0 g day^{-1} m^{-2} as $CaCO_3$ and the 6 g day^{-1} m^{-2}

Table 1. Removal Rate (g day^{-1} m^{-2}) for Fe^{+3} Using Zero-order Model.

Cumulative Treatment Area

Wetland	64 m^2	96 m^2	128 m^2	256 m^2	374 m^2
1	nd	nd	1.01	+0.03	1.34
2	nd	3.04	1.21	+0.87	1.13
3	nd	nd	1.15	-0.03	2.92
4	2.90	nd	1.72	-.036	0.35
5	nd	nd	1.25	+0.55	1.67
6	1.93	nd	0.35	-0.45	12.10

Table 2. Removal Rate (g day^{-1} m^{-2}) for Fe^{+3} Using First-order Model.

Cumulative Treatment Area

Wetland	64 m^2	96 m^2	128 m^2	256 m^2	374 m^2
1	nd	nd	1.08	+0.04	0.71
2	nd	4. 93	0.38	+0.85	0.79
3	nd	nd	1.47	-0.02	0.52
4	5.90	nd	4.44	-0.33	0.17
5	nd	nd	3.78	-0.03	0.77
6	1.28	nd	0.81	-0.03	0.54

Table 3: Removal Rate (g day^{-1} m^{-2}) for Al^{+3} Using First-order Model.

Cumulative Treatment Area

Wetland	64 m^2	96 m^2	128 m^2	256 m^2	374 m^2
1	nd	nd	4.42E-01	-2.42E-02	-1.50E+00-
2	nd	3.09E+00	2.20E-01	-1.07E-02	-2.93E-01
3	nd	nd	4.58E-01	-2.30E-03	-1.19E+00
4	3.64E+00	nd	5.58E-01	+1.22E-01	-4.13E-01
5	nd	nd	2.08E+00	-1.66E-03	-1.30E-01
6	9.80E-01	nd	3.89E-02	+7.28E-02	-7.85E-01

In all three tables, the symbol "nd" means "not determined."

guideline given by Dietz *et al.* (1994). We conclude that the sizing guidelines for a system of this type receiving acidic influent can be explained by simple kinetic models. The designer is cautioned that the wetlands will experience a transient startup period, during which a steady model will not apply. Desorption of pollution indicators from the substrate during the transient startup period, particularly Mn, appears to be important, and the simplified models should not be applied to this period.

The declining performance of the wetlands indicated that the acid neutralizing properties of a substrate fashioned only of horse manure and inert, preponderantly SiO_2 stone will not be sustained for more than about 1 to 1½ year.

The performance of wetlands designed in a specific way to take advantage of anaerobic processes for treating a mine discharge with moderate acidity and moderately elevated metals has been studied. Water quality data have been presented representing the first 806 days of operation, including transient startup conditions and short term performance following startup. Long-term data continue to be collected. The flow patterns in the wetlands were studied with a Br^- tracer, and the presence of flow through the substrate was demonstrated. Anhydrous NH_3 as pretreatment has the effect of accelerating the hydrolysis of Fe^{+3} and thus has the advantages of chemical treatment with other alkaline materials. The simple mathematical models we have developed compare favorably with previous design criteria. Further modeling efforts continue, and the results of this effort will be presented at a later time.

Literature Cited

Commonwealth of Pennsylvania, Department of Environmental Protection (formerly Department of Environmental Resources),1988. *Water Quality Assessment.* Harrisburg PA, USA.

Hellier, W.W., E.F. Giovannitti, and P.T. Slack, 1994. "Best professional judgment analysis for constructed wetlands as a best available technology for the treatment of post-mining groundwater seeps. *International Land Reclamation and Mine Drainage Conference and third International Conference of the Abatement of Acidic Drainage.*, Vol. I, Proceedings of a conference held in Pittsburgh PA, USA, on April 24-29, 1994. US Department of the Interior, Bureau of Mines, Special Publication SP-06A-94.
https://doi.org/10.21000/JASMR94010060

Skelly and Loy Engineers, 1972. *Engineering report: Muddy Run Watershed mine drainage study, project no. SL 155.* Report to the Commonwealth of Pennsylvania, Department of Environmental Resources, Harrisburg PA, USA.

US Environmental Protection Agency, 1982. *Development Document for Effluent Limitation Guidelines for the Coal Mining Point Source Category.* EPA 440/1-82/057. 407p. Washington DC, USA.

Hedin, R.S., R.W. Nairn, and R.L.P. Kleinmann, 1994. *Passive Treatment of Coal Mine Drainage.* US Bureau of Mines Information Circular IC 9389. Washington DC, USA. Table 19,25.

American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1992. *Standard Methods for the Examination of Water and Wastewater,* 18th Edition. American Public Health Association, Washington DC, USA.

Donahue, T.C., 1994. *A Hydrologic Tracer Investigation of the Bark Camp Constructed Wetlands.* A paper in environmental pollution control presented in partial fulfillment of the requirements for the Degree of Master of Engineering, Pennsylvania State University, University Park PA, USA.

Hellier, W.W., 1996. The Bark Camp Run Demonstration Constructed Wetlands: Findings and Recommendations for Future Design Criteria. Final Report to the United States Environmental Protection Agency. PA Department of Environmental Protection, Harrisburg PA, USA. 696 p.

Dietz, J.M., R.G. Watts, and D.M. Stidinger, 1994. Evaluation of Acidic Mine Drainage Treatment in Constructed Wetlands. *International Land Reclamation and Mine Drainage Conference and third International Conference of the Abatement of Acidic Drainage.*, Vol. I, Proceedings of a conference held in Pittsburgh PA, USA, on April 24-29, 1994. US Department of the Interior, Bureau of Mines, Special Publication SP-06A-94, 70-79.
https://doi.org/10.21000/JASMR94010070