STAGED, AEROBIC CONSTRUCTED WETLANDS TO TREAT ACID DRAINAGE - THE TENNESSEE VALLEY AUTHORITY PROGRAM

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ABSTRACT

The Tennessee Valley Authority has constructed 14 staged, aerobic constructed wetlands to treat acid drainage at reclaimed coal mines, a coal preparation plant, and at coal-fired power plants. Nine Systems produce consistent compliance quality discharges without chemical treatment. The other systems are either under development or are not in compliance due to high Fe and zero alkalinity in the inflow which result in low pH due to Fe oxidation and hydrolysis in the wetlands. These systems are being modified with anoxic limestone drains (ALD) to increase alkalinity of the inflow to buffer against pH decreases. one high Fe, zero alkalinity system has been in compliance since May 1990 when an ALD was added above the wetlands. TVA's wetlands rely on oxidative mechanisms in cattail (Typha sp.) marsh-pond type wetlands cells in addition to aeration structures and anoxic mechanisms in the ALDs. Systems are currently removing Fe at rates between 0.4 and 21.3 grams/day/m2 of wetlands (GDM) and Mn at rates between 0.15 and 1.87 GDM. TVA's wetlands have been loaded at rates 0.03

-41.5 GDM for Fe and 0.17 - 2.0 GDM for Mn. All of the wetlands meet compliance for total suspended solids. Based on TVA's operational results, design recommendations have been developed.

In May 1985, the Impoundment 1 wetlands was constructed to treat acid drainage emanating from an earthen dam impounding fine coal refuse at TVA's Fabius Coal Preparation Plant in Alabama. The system has consistently discharged compliance quality water and reduced total Fe from 69 mg/1 to 0.9 mg/1 and total Mn from 9.3 mg/1 to 1.6 mg/l. Suspended solids has always been in compliance. The pH has effectively been increased from 3.5 to 6.8 primarily due to a limestone roadbed located under the earth dam. Aquatic flora and fauna in the constructed wetlands and receiving stream have shown rapid growth, expansion, and diversification.

INTRODUCTION

Staged, aerobic constructed wetlands offer an inexpensive, natural, low maintenance, and potentially a long-term solution to treating acid drainage without chemical additives.[1] Since 1985 the Tennessee Valley Authority (TVA), the Nation's largest electric utility, has constructed 14 wetlands systems for treating acid drainage at coal mining and processing facilities and coal-fired power plants. Twelve of these sites are now operational (one is under development and one was abandoned), and have been evaluated and manipulated in attempts to understand and refine the processes occurring in constructed wetlands. Nine of the 12 operational systems are meeting water discharge limitations without any chemical treatment.

METHODOLOGIES

Guidelines for design, construction, and operation of aerobic acid drainage treatment wetlands have been developed.[2] These should be considered comprehensive due to the continued upgrading of the constructed wetlands technology and the need for site specific designs which often restrict the use of standard engineering and construction methods. Detailed descriptions of the design, preliminary considerations, and construction of TVA's wetlands have been published elsewhere.[1,2,3]

Design and construction

Figure 1 shows a typical plan for a constructed wetlands. TVA's aerobic wetlands generally consist of a pretreatment stage (anoxic limestone drain and/or oxidation basin) followed by several cells of shallow to deep (0.1 -2.0 m) cattail (*Typha sp.*) marsh-ponds. Most of the systems have been constructed in groundwater gaining streams created by the acid drainage, although a few sites required diversions to rout the drainage to the wetlands system. Some systems are followed by a final polishing pond which may improve long-term capacity and minimize storm event flushing of Fe and Mn precipitates from a constructed wetlands.[4]

Based on TVA's results only, aerobic wetlands systems should be designed for 4.0 - 11.0 GDM of Fe removal depending on pH, alkalinity, and Fe concentrations of the inflow.[2] TVA's early wetlands systems (i.e., those before 1988) were sized hydraulically and then increased if the site allowed. Cell areas were arbitrarily increased in size if very poor quality water was to be treated. The most recent wetlands have been sized based on state-of-the-art guidelines,[2] but in most cases have been built larger than design size to increase the safety factor and lifespan of the systems.

To ensure long-term stability, dikes were sloped no steeper than 2:1 and riprapped or protected with erosion-control fabric on the slopes. Spillways were designed for handling the maximum probable flow with an ample safety factor and protected with either large (> 30 cm) riprap or non-biodegradable erosion-control fabric planted with species such as wool grass (Scirpus cyperinus), sedge (Carex sp.), or threesquare (Scirpus americanus). Recent wetlands spillways have been designed using very large riprap (>50cm) to provide subsurface flow through the dike to discourage beaver activity.

Wetlands shapes varied and were dictated by existing topography, geology, and- land availability. The number of cells was determined by site topography, hydrology, and water quality. Level sites were amenable to large cells hydraulically chambered with rock or earthen finger dikes, large logo, or vegetated hummocks. Steeper slopes required more grading, or a system of several cells terraced downgrade. At least one wetlands cell was constructed for each 50 mg/1 Fe in the inflow due to the need for reaeration after oxidation of this amount of Fe.

Average water depth in TVA's wetlands ranged from 15-30 cm with some deeper and shallower areas to provide for species diversification. Isolated deep pockets of up to 2.0 m were included in many cells to provide for aquatic fauna refuge in drought events.

Vegetation was hand dug to obtain complete root balls/rhizomes and planted on the same day as digging. Cattail (Typha sp.) was set into the substrate at 0.3 m centers in early systems and 1.0 m centers in later ones. Stems were broken over at the water level to prevent windfall and to stimulate new growth from the rhizomes. Recent large wetlands have been planted by scattering cattail seeds. Results of this methodology are pending. Wool grass (Scirpus cyperinus), sedge (Carex sp.), and rush (Juncus effusus) clumps were simply placed in the desired location. Squarestem spikerush (Eleocharis quadrangulata) and scouring rush (Equisetum hyemale) were carefully set into the substrate. Complete wetlands installations were operating in 6 to 10 weeks depending on their complexity. Most wetlands were completed in early summer, although successful installations were completed as late as October. Wetlands were fertilized generally only once with a phosphorous-potassium fertilizer such as 0-12-12 at 400 kg/ha.

Mosquitoes have not been a problem at TVA's wetlands, however, as a precaution mosquitofish (Gambusia affinis) were stocked in all wetlands. Several bat houses have been installed at TVA to investigate the use of bats for mosquito control. Additionally, various bird houses (martin, screech owl, wood duck, blue bird) were erected at the sites.

Post-construction activities included water quality monitoring, maintenance of dikes and spillways, and the addition of new ponds to further treat the wetlands discharge. Additional water, substrate, and vegetation sampling and biological monitoring was performed to quantify the wetlands development and treatment efficiencies.

Sampling and Analytical Techniques

NPDES monitoring requirements included pH, total Fe and Mn, and total suspended solids (TSS). Effluent samples from the wetlands were obtained during daylight hours generally within the second and fourth weeks of the month. Sampling was always initiated within two weeks of system startup. All samples were collected and analyzed according to standard methods.

Total metals samples were collected in 500 ml acid-rinsed polyethylene bottles, preserved with HNO^3 to a pH of greater than 2.0, usually by tilting the bottle gently into the seep. The sample was placed on ice and transported to the laboratory for analyses. Samples were digested with concentrated, redistilled HNO^3 and HCl, reduced to 20 ml, diluted back to volume, centrifuged or filtered depending on solids, and then analyzed by atomic emission or atomic adsorption.

Total suspended solids (TSS) samples were collected in one-liter cubitainers. All air was expelled from the cubitainer and the sample was stored on ice for transport to the lab. Samples were filtered through glass fiber-filter, dried at 102 to 1059C with the difference of weight retained on filter and reported as TSS.

RESULTS

A summary of characteristics and water quality parameters for TVA's 14 constructed wetlands is presented in Table 1. Significant water quality improvement has occurred at all of the 12 operating wetlands. Nine systems have produced discharges that consistently meet NPDES monthly average discharge limitations (pH = 6 - 9 s.u.; Fe < 3.0 mg/l; Mn < 2.0 mg/l; TSS < 35.0 mg/1) with no chemical treatment. Where regulatory limits were not entirely achieved, Cost savings were realized as a reduction in chemicals needed for further metals precipitation or pH adjustment at IMP2, WCF6, and COF13. TVA's wetlands were, on average, hydraulically loaded between 0.02 - 0.24 l/day/m2 of wetlands (LDM). Maximum hydraulic loading ranges were 0.06 - 1.47 LDM and averaged 0.42 LDM.

Ten of the 12 operating wetlands produce discharges in compliance with total Fe limitations, i.e., < 3.0 mg/l (Table 1). Figure 2 shows Fe loading in the systems ranges from 0.03 GDM to 41.4 GDM. Fe removed ranges from 0.0 GDM to 21.3 GDM, corresponding to 0 to 99 % Fe removal. Note that the 0 % removal is associated with very low Fe inflow (0.7 mg/1) at the COF wetlands; this data may be a result of sampling error or a lower limit of Fe removal possible at the COF wetlands. Fe removal in the wetlands is very efficient for loadings up to 13 GDM which occurs at the WCF6 wetlands. Fe removal has been efficient (51 %) at KIF where Fe loading exceeds 41 GDM. However, with the addition of an ALD at KIF 006 and with the resultant hydrologic changes, Fe loading at KIF has been about 8.1 GDM with about 93% removal. More data for Fe loadings between 13 GDM and 41 GDM is needed to better assess the Fe loading limit for a constructed wetlands. There is no correlation in TVA's wetlands between Fe removal and influent alkalinity, Fe removal and wetlands size, or Fe removal and hydraulic loading.[1]

Figure 3 shows total Mn loading and removal in the TVA wetlands. Data for WCF5 is not available. Nine of the twelve operating wetlands produce discharges in compliance with total Mn limitations, i.e., < 2.0 mg/1 (Table 1). Mn loading ranges from 0.17 GDM to 2.00 GDM. Mn removed ranges from 0.15 GDM to 1.87 GDM, corresponding to 0 to 96% Mn removal. The low removal rates are all associated with low pH (2.9 - 3.9 s.u.) systems. Mn removal in the wetlands is very efficient for loadings as high as 2.0 GDM, which occurs at the 950NE wetlands. There is no correlation in TVA's wetlands between Mn removal and wetlands size, and Mn removal and hydraulic loading. There is a good correlation between Mn removal and influent alkalinity and acidity concentrations (Figure 4).[l,3] Systems with zero alkalinity have removed 0 to 16.5% Mn, while systems with alkalinity greater than 62 mg/l and with excess acidity as high as 248 mg/1 have removed 85-97% of the Mn load. Inflows with zero alkalinity have always resulted in low pH in the wetlands. Low Mn removal is associated with zero alkalinity and thus, low pH in the wetlands. This data suggests that Mn co-precipitation on Fe-oxides at circum-neutral pH is a likely mechanism of Mn removal.[5]

Nine of the twelve systems increase or maintain inflow pH to produce discharges in compliance for pH, i.e., 6.0 - 9.0 (Table 1). Three systems cause pH reductions due to Fe oxidation and hydrolysis; these systems are being modified with anoxic limestone drains.[3] All of the wetlands produce discharges in compliance with total suspended solids (TSS) limitations, i.e., < 35 mg/l.

Case History of Impoundment 1 Constructed Wetlands

Impoundment 1 (IMPl), constructed in June 1985, was TVA's first acid mine drainage treatment wetlands. The system treats acid seepage emanating from an earth dike impounding 16 ha of coal slurry at TVA's reclaimed Fabius Coal Preparation Plant in Jackson County, Alabama. Since construction IMPI has generally produced compliance-quality effluent. Figure 5 shows average water quality data during the period July 1985 to October 1991 for the wetlands inflow and the discharges from each of the four wetlands cells. Variations in flow from each cell were due, in part, to acid seeps encountered along a sandstone shelf underlying the site and in the leaky nature of the wetlands system. Effluent from the first cell alone has met discharge limitations 56 percent of the time. Figure 6 shows total Fe and total Mn concentrations in the effluent for the same period. From June to August 1988 and again from June to September 1989, total Mn concentrations increased to several times the IMP1 average discharge concentration of Mn. Similar but less drastic increases in Mn concentrations were noted in the summers of 1986 and 1987. When these anomalies were compared to rainfall records and wetlands flow, no correlations were apparent. Most of the other wetlands have exhibited similar patterns of Mn concentration variability. These increases are probably seasonally related and could be due to numerous factors, including temperature, degree of mixing, redox conditions, nutrient and/or carbon availability, or photosensitivity of Mn-oxidizing bacteria.

IMPI is one of two constructed wetlands receiving inflow total Fe concentrations exceeding 50 mg/l that successfully produces compliance-quality discharges without chemical treatment. Other wetlands receiving greater than 50 mg/l total Fe **(Table 1) have** been impacted by low pH, high acidity, and the resultant inability to remove Fe and/or Mn to meet discharge limitations. Investigations into differences among the wetlands revealed that IMP1 influent had an alkalinity often exceeding 250 mg/l. The three other high-Fe wetlands had influent alkalinity ranging from 0 to 26 mg/l with high acidity. Further investigations into the IMP1 characteristics disclosed that the leaking coal slurry impoundment dike was constructed in 1974 over an existing limestone coal mine haul road, which may represent the oldest, working anoxic limestone drain (ALD).3 Historically, local limestone has been quarried from the Monteagle Formation, an oolitic, high-calcium carbonate limestone. Apparently this road is the source of the IMP1 influent alkalinity.

Stability problems at IMPI resulted from inadequate spillway and dike designs. Each dike was repaired in late 1989 to increase the freeboard to over 30 cm. The spillways were reconstructed to provide long-term, erosion-resistant stability. Six species were originally planted in IMPl: broadleaf cattail (Typha latifolia), wool grass (Scirpus cyperinus), rush (Juncus effusus), scouring rush (Equisetum hyemale), and squarestem spikerush (Eleocharis quadrangulata). Over 70 vegetative species have now been identified in IMP1, dominated by Typha latifolia, Scirpus cyperinus, Juncus effusus, Eleocharis quadrangulata, and rice cutgrass (Leersia oryzoides). The remaining stream of IMPI originally was almost biologically dead (less than 5 invertebrate species). The stream now contains over 30 species of invertebrates as well as mosquitofish (Gambuzia affinis) and other minnow species.

Total cost of the IMP1 wetlands was $43,000 (1985 dollars). Annual Costs from 1985-1990 were about $13,000 due to repairs on the prototype design and due to extensive monitoring. operations and maintenance costs today are less than $1,000 annually. Costs to chemically treat this acid drainage site instead of with wetlands treatment would have been approximately $250,000 from 1985 to 1991.

SUMMARY AND CONCLUSIONS

TVA has constructed 14 and operates 12 aerobic, staged wetlands systems for treating acid drainage from coal mine spoil, coal slurry and gob, and coal ash. These systems offer a preferred alternative to conventional methods of treating acid drainage from various coal-related sources.

Nine wetlands systems now produce effluents meeting all discharge limitations without chemical treatment, four of which have been released from NPDES monitoring requirements. These 9 systems are associated with moderate inflow water quality (i.e., total Fe = 0.7 - 69 mg/l, total Mn 5 - 17 mg/1), relatively high total Mn to total Fe ratios in the influent (average Mn/Fe = 0.44), significant inflow alkalinity (35 - 300 mg/1), and variable Fe loading (.03 - 6.13 GDM).

Five systems have experienced high acidity production and low pH within the wetlands due to Fe oxidation/hydrolysis. Four of these systems are associated with high influent Fe concentrations (40-170 mg/1), high Fe loads (5 - 41 GDM), and zero to very low influent alkalinity. Two of these wetlands discharges require NaOH treatment to achieve compliance quality. One system, Imp4, was modified with an anoxic limestone drain which has allowed cessation of chemical treatment and enabled the wetlands to produce compliance quality discharges. Another system, KIF6, has been modified with an anoxic limestone drain, but due to its recent completion (10/l/91), only preliminary data has been collected.

One system (COF) which has experienced very little metals reduction is associated with low Fe (0.7 mg/1) and higher Mn (5.3 mg/1). The performance of this wetlands may be related to absence or inhibition of Mn-oxidizing bacteria or lack of Fe-Mn coprecipitation. TVA is currently investigating the use of rock filters to lower concentrations of Mn in low Fe acid drainage.

Fe and Mn removal efficiencies and pH improvement in the TVA wetlands do not correlate well with wetlands treatment areas for total Mn or flow. This, in part, is probably due to the effect of Fe oxidation/hydrolysis overwhelming other wetlands system mechanisms.

Many factors affect the ability of wetlands to ameliorate acid drainage, including hydrology, Fe and alkalinity concentrations, and various wetlands characteristics such as depth, area, hydraulics, vegetative and microbial species and extent, and substrate. Because of the interrelationships among these many factors and their effects on wetlands treatment efficiencies, it is difficult to develop treatment area design guidelines. Additionally, with the relatively new concept of the anoxic limestone drain, required areas and designs of wetlands to achieve compliance may be greatly affected. However, TVA's data show that even in the absence of alkalinity, wetlands are removing up to 21.3 GDM of Fe. Mn is being removed up to 1.9 GDM in the presence of alkalinity. TVA's experience suggests that these numbers may represent an upper limit sizing criteria for aerobic wetlands as they are currently designed and constructed.

TVA's encouraging results suggest that staged treatment wetlands systems are preferred designs potentially capable of treating poor-quality acid drainage. Such staged treatment may consist of: 1) an initial anaerobic limestone trench at the source of the seepage to passively add alkalinity; 2) a large, deep settling basin to accumulate oxidized and precipitated Fe sludges; and 3) a two or three cell constructed wetlands for Mn and further Fe removal. TVA is currently investigating the use of passive alkaline beds to increase the pH of constructed wetlands discharges in cases where pH remains below 6.0. TVA plans to continue its research and evaluation of operational and experimental wetlands treatment systems, especially regarding methods to passively increase buffering capacity and pH in wetlands influents and effluents. As more information is made available by TVA and other operating systems and research activities, design guidelines for the components of staged-treatment wetlands systems should be improved.

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TABLE 1

TVA ACID DRAINAGE WETLANDS TREATMENT SUMMARY

Wetlands System	Date Initiated Operation	Area m^2	Number Cells	Influent Water Parameters (mg/L) pH	Fe	Mn	TSS	Effluent Water Parameters (mg/L or L/min) pH	Fe	Mn	NFR	Flow Ave	Flow Max	Loading g/day/m^2 Fe	Mn	1/day/m^2 Ave Flow
950	1-76	3400	3	5.7	12.0	8.0	20.0	6.5	1.1	1.6	5.4	83	341	.42	.28	.04
IMP1	7-85	5700	4	6.1	69.0	9.3	9.5	6.7	0.9	1.8	3.0	73	693	1.27	.17	.02
IMP4	11-85	2000	3	6.3	65.0	16.8	21.0	6.3	0.4	0.6	6.0	131	693	6.13	1.58	.09
WCF5	7-90	6600	4	-	-	-	-	8.4	2.2	0.7	-	973	2057	-	-	.21
WCF6	6-86	4800	3	5.6	150.0	6.8	-	3.9	6.4	6.2	-	289	1495	13.0	.59	.09
WCF19	6-86	25000	3	5.6	17.9	6.9	-	4.3	3.3	5.9	-	492	6360	.50	.20	.03
IMP2	6-86	11000	5	3.5	40.0	13.0	9.0	3.1	3.4	13.0	0.8	1016*	1540*	5.32	1.72	.13
IMP3	10-86	1200	3	6.3	15.8	4.9	21.4	7.0	0.5	0.7	9.0	58	250	1.10	.34	.07
RT2	9-87	7300	3	5.7	45.2	13.4	-	6.8	0.6	1.8	3.2	277	1155	2.47	.73	.05
950NE	9-87	2500	4	6.0	11.0	9.0	19.0	6.9	0.6	0.8	5.0	385	1386	2.44	2.00	.22
KIF6	10-87	9300	3	6.6	204.0	14.0	40.0	3.8	16.0	10.0	-	262	-	41.43	1.07	.24
COF	10-87	9200	5	5.7	0.7	5.3	-	6.7	0.7	3.5	-	288	408	.03	.24	.05
DLL	5-90	7550	4	6.2	10.0	5.5	23.0	6.4	2.1	2.2	10.0	385	7700	.73	.40	.07
HR000	UC**	40,000	5	5.5	40.0	17.0	-	-	-	-	-	4000	-	-	-	-

*Also receives pumpage from slurry lake up to 4800 1/min.
**Under Construction

3659f

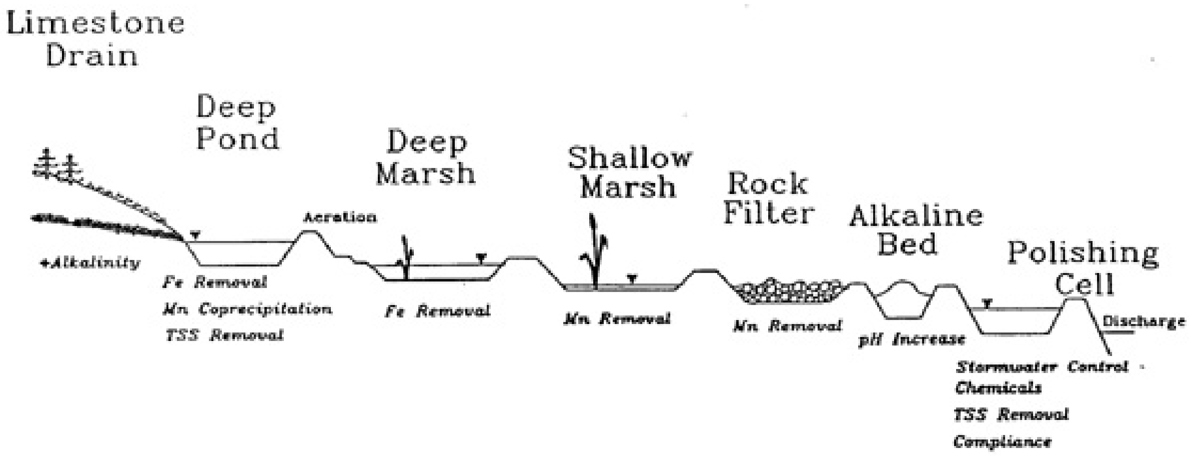


Figure 1

Typical Plan for Aerobic Constructed Wetlands

Figure 2. Fe Loading and Removal

TVA Constructed Wetlands

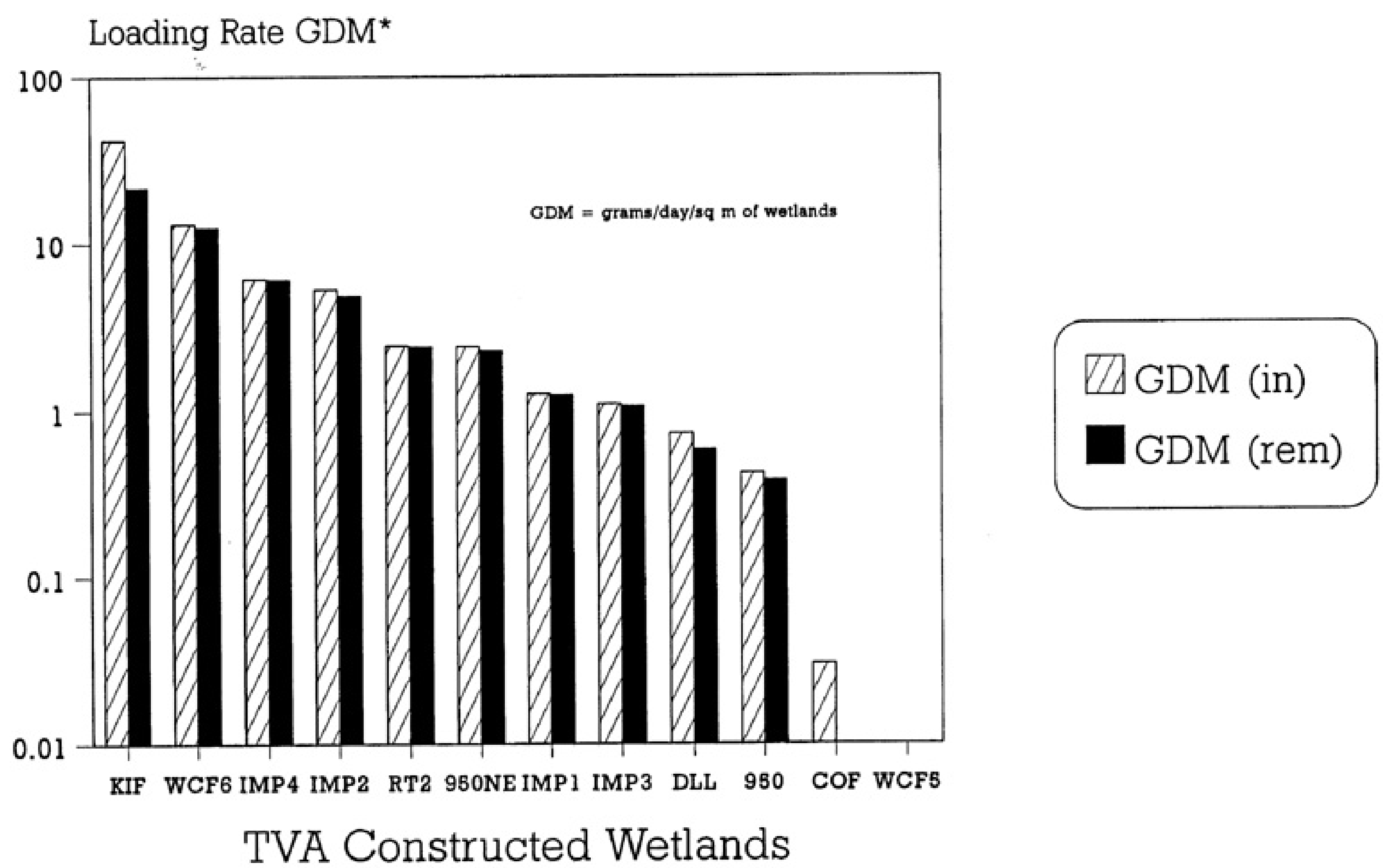


Figure 3. Mn Loading and Removal in TVA Constructed Wetlands

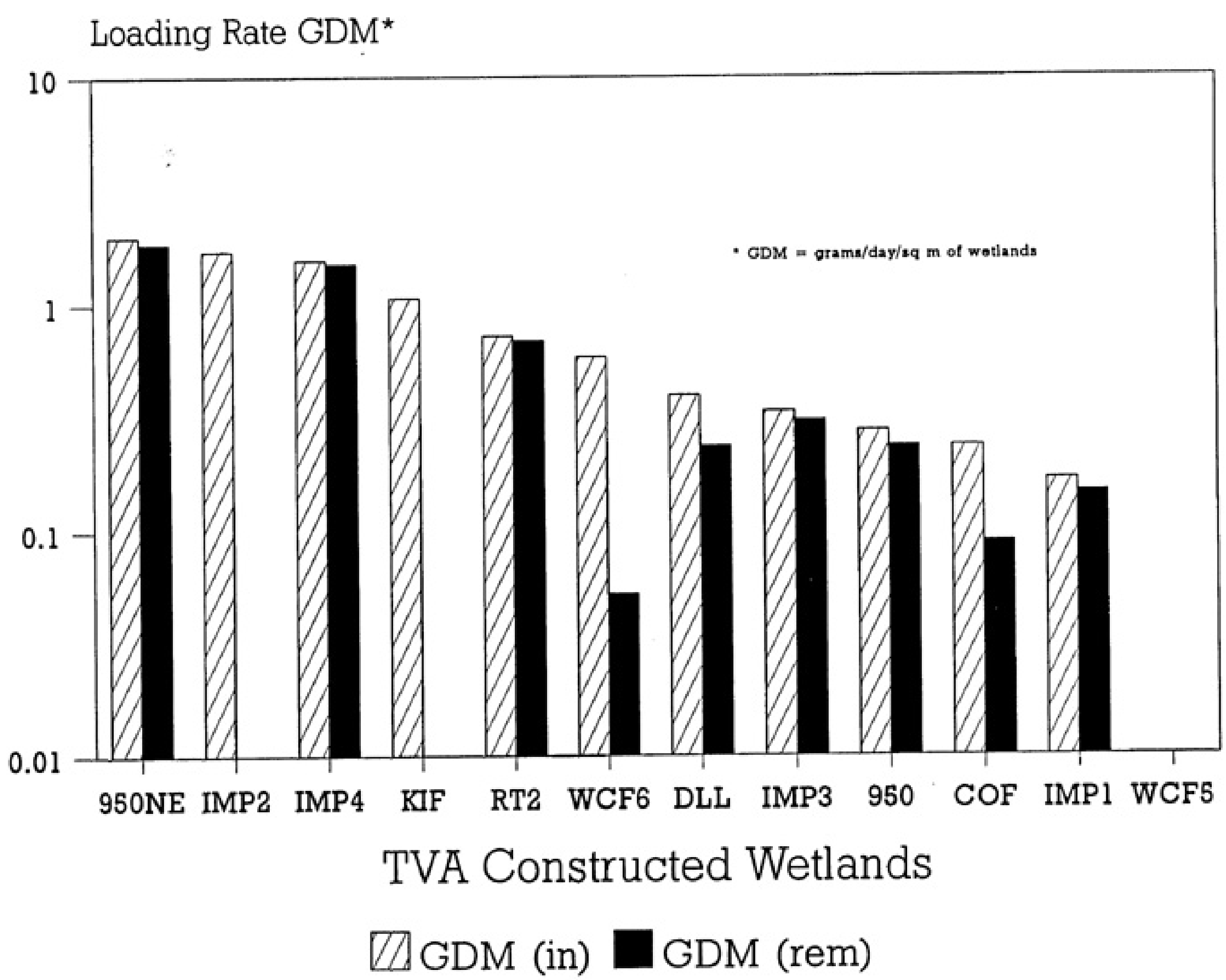


Figure 4. Mn Removal Related to Inflow Alkalinity
TVA Constructed Wetlands

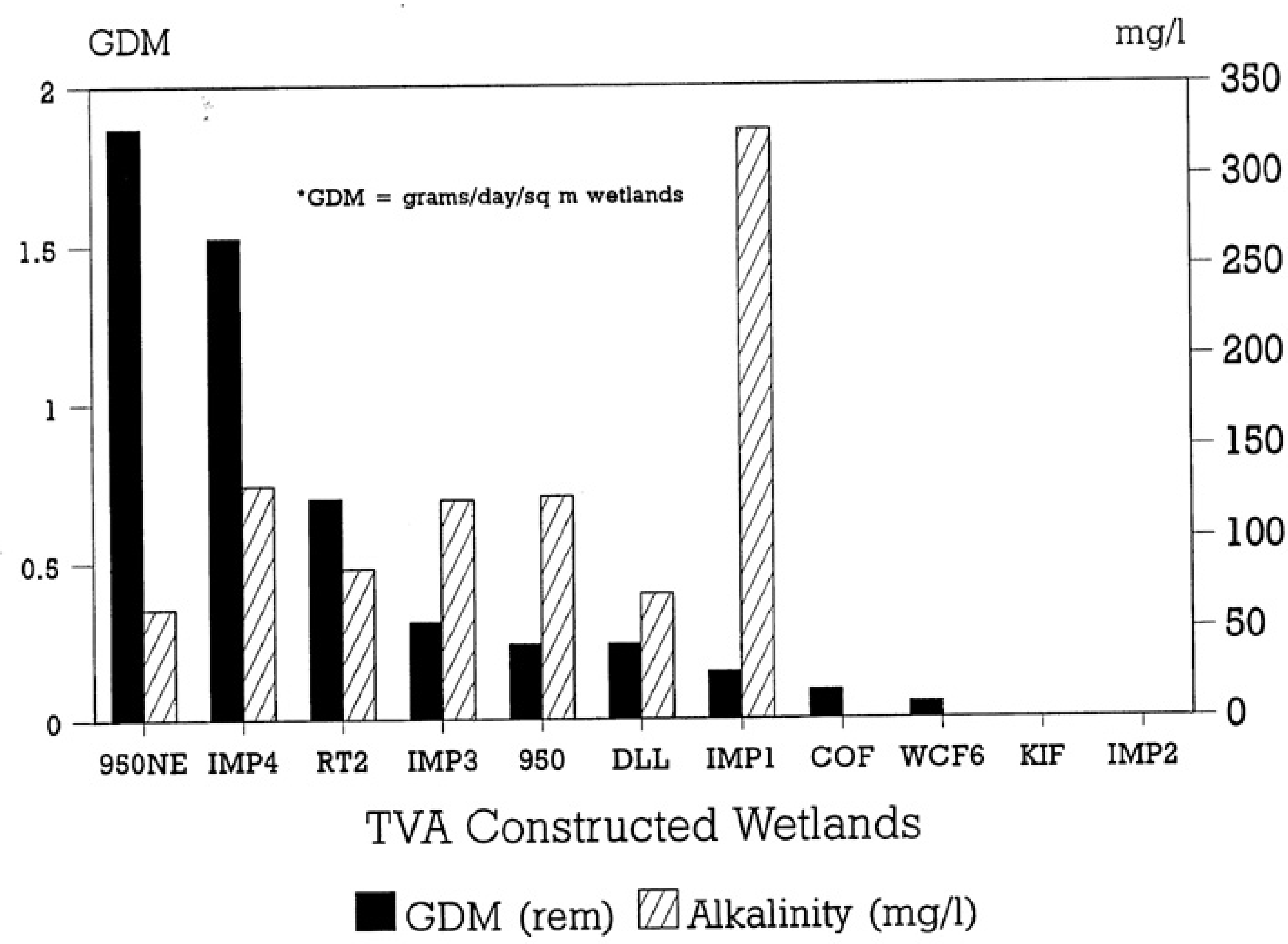
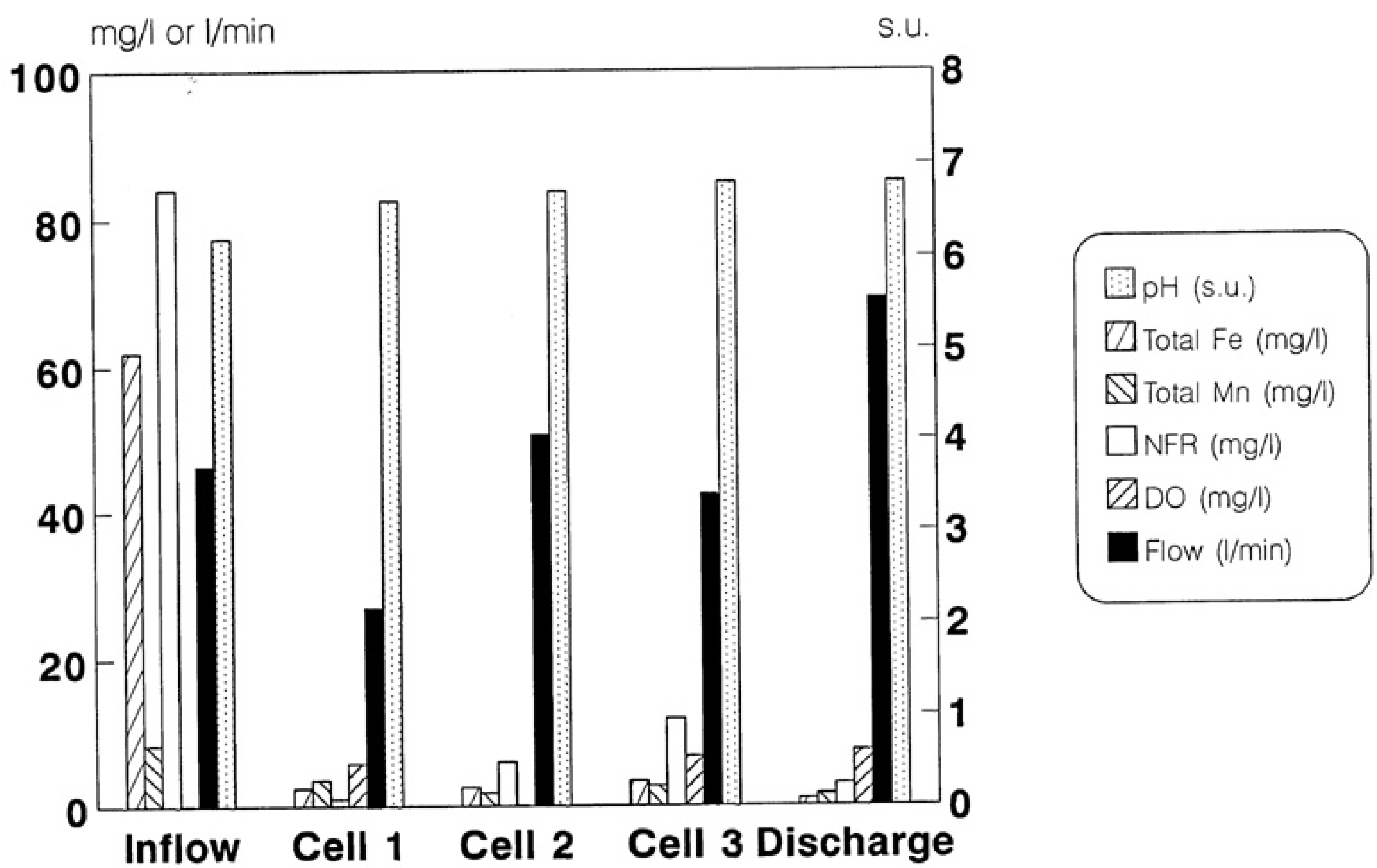


Figure 5. Fabius IMP1 Constructed Wetlands

Average Effluent Data



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Total Fe and Total Mn Effluent Concentrations