ACHIEVING COMPLIANCE WITH STAGED, AEROBIC, CONSTRUCTED WETLANDS TO TREAT ACID DRAINAGE[1]

by

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__Abstract.__ The Tennessee Valley Authority (TVA) operates 12 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. Four systems not achieving compliance have high Fe (e.g., > 100 mg/l) and zero alkalinity in the inflow that results in low pH due to Fe hydrolysis in the wetlands. These systems are being modified with anoxic limestone drain (ALD) pretreatment components 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 prior to the wetlands. TVA's wetlands rely on oxidative mechanisms in cattail (__Typha spp__.) 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/m^2 of wetlands (GDM) and Mn at rates between 0.15 and 1.87 GDM. TVA's wetlands have been loaded at rates of 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.

Additional Key Words: Iron, manganese; buffering capacity; ash disposal; alkalinity

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Introduction

Constructed wetlands offer an inexpensive, natural, low-maintenance, and potentially long-term solution to treating acid drainage without chemical additives (Hedin 1989; Brodie 1990a,b). Since 1985, the Tennessee Valley Authority (TVA), the largest electric utility in the United States, has constructed 13 aerobic, staged, wetlands systems for treating acid drainage at coal mining and processing facilities and coal-fired power plants. Twelve of these sites, along with 2 separate research facilities, are now operational and have been evaluated in attempts to understand and refine the processes occurring in constructed wetlands.

Discussion

Guidelines for design, construction, and operation of aerobic, acid drainage treatment wetlands have been developed, although none should be considered comprehensive due to continued upgrading of the constructed wetlands technology (Kleinmann et al 1990; Reed et al 1988; Brodie 1990c). Wetlands require design for specific conditions because site characteristics restrict the use of standard engineering and construction methods.

Preliminary Considerations

Wastewater characterization and site hydrology were the two most important predesign data needs. Baseline water quality and flow were established for all source waters to be treated and for receiving streams to document existing conditions and evaluate the operational treatment system. Minimum analyses included pH, oxidation-reduction potential (ORP), total and dissolved Fe and Mn, total suspended solids, sulfate, dissolved oxygen (DO), alkalinity, acidity, and Al. Sampling should be performed on unaerated seepage to obtain representative values of DO and ORP, 2 parameters which are critical in determining the practicality for an anoxic limestone drain (Turner and McCoy 1990; Brodie et al 1990, 1991). Qualitative baseline surveys of aquatic biota in receiving streams were conducted at some sites to provide a means of documenting stream recovery. Flow patterns and depth to groundwater were characterized to identify inflows or outflows that could affect water quality or hydrologic balance.

Wetlands were often located off a permitted area or leased/owned surface. Thus, negotiations with landowners for initial access and long-term leases or easements were necessary. Topographic data were obtained in sufficient detail to plan the number and location of cells to minimize cut and fill requirements. Detailed topographic surveys were not usually warranted.

Geologic data were evaluated to determine if the site overlay shallow bedrock or lacked suitable growth media. If necessary, sources of borrow were identified for construction materials. Wetlands substrates at all systems (except KIF6) consisted of local or in-situ materials and no additional substrate was imported.

Vegetation sources for transplantation into the constructed wetlands were identified. Sources included nearby wetlands and commercial nurseries. Cattail (Typha spp.), for deep water, (0.2 - 0.5 m) and rush (Eleocharis spp.); water sedge (Carex spp.); threesquare (Scirpus americanus); and wool grass (Scirpus cyperinus), for shallow water, (< 0.2 m) were the most tolerant, readily available species for transplantation. Another rush (Juncus effusus) was used with less success. Broadleaf cattail (Typha latifolia) and squarestem spikerush (Eleocharis quadrangulata) may provide higher radial oxygen loss than other common species, thereby enhancing substrate oxidizing conditions to bind insoluble forms of metal precipitates in the substrate (Copeland 1988).

Design and Construction

Figure 1 shows a typical schematic for an aerobic 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 spp.) marsh-ponds. Most of have been constructed in streams created by the acid drainage, although a few sites required diversions to route drainage to the wetlands system (e.g., 950 NE). Some systems are followed by a final polishing pond (e.g., IMP4), which may improve long-term capacity and minimize storm event flushing of Fe and Mn precipitates from a constructed wetlands (Brodie and Taylor 1991).

Early constructed wetlands were sized based on hydraulic loading (Kleinmann et al 1986; Girts et al 1987). Recently, chemical loading has been suggested as the primary design criteria for wetlands sizing. Chemical loading can be expressed in grams/day/m^2 of wetlands (GDM) for specific chemical species (e.g., Fe, Mn, alkalinity, or acidity). Chemical loading rates have been suggested for sizing wetlands, but are difficult to develop and should be considered preliminary until further studies are completed (Stark et al 1990; Brodie 1990c; Kepler et al 1990; Hedin and Nairn 1990) TVA's wetlands are, on average, hydraulically loaded between 0.02 - 0.24 l/day/m^2 of wetlands (LDM). Maximum hydraulic loading ranges are 0.06 - 1.47 LDM and the average is 0.42 LDM. Chemical loading ranged from .03 - 41.5 GDM for Fe, and .17 - 2.0 GDM for Mn. Based on TVA's wetlands results only, aerobic wetlands systems should be designed for 2.0 - 11.0 GDM of Fe depending on pH, alkalinity, and Fe concentrations of the inflow (Brodie 1990c). TVA's early wetlands systems (i.e., those in use 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 Brodie (1990c), 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 a 100 yr, 6 hr event with a safety factor of 3 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 spp.), or threesquare (Scirpus americanus).

Wetlands shapes varied and were dictated by existing topography, geology, and land availability. Irregular shapes for wetlands cells enhanced their natural appearance and provided hydraulic discontinuity. Configurations were avoided that could increase flow velocities and cause channelization, scouring, or bank erosion.

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 logs, or vegetated hummocks. Steeper gradients required more grading or a system of several cells terraced downgrade. Staged treatment using several cells may provide a more efficient system since chemical and hydraulic overloading of all cells would be minimized. It has been suggested that one cell should be constructed for each 50 mg/l Fe inflow due to the need for reaeration after oxidation of this amount of Fe (Kleinmann 1990).

Water depth and bottom slope were dependent on desired plant species, pollutant concentrations, freeze potential, and desired longevity of the system. 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.

Wetlands construction began with site clearing and grading with dozers, followed by dike and spillway construction with backhoes or hydraulic excavators. The wetlands was then flooded and planted. Vegetation was hand dug to obtain complete root balls/rhizomes and planted on the same day as digging. Plants were not subjected to extreme temperatures, drying, or wind during transport. Cattail (Typha spp.) was set into the substrate and stems broken over at the water level to prevent windfall and to stimulate new growth from the rhizomes. Wool grass (Scirpus cyperinus), sedge (Carex spp.), 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. One system planted in November required replanting. Wetlands were fertilized with a phosphorous-potassium fertilizer such as 0-12-12 at 400 kg/ha. Fertilization beyond the first year was done only if the vegetation showed signs of nutrient depletion.

Mosquitos have not been a major problem at TVA wetlands except at the newest site, DLL. Several species of annoying biters (*Anopheles punctipennis*, *A. quadriumaculatus*, and *Culex erraticus*) have been identified in TVA wetlands. Additionally, *Psorophora columbia* and *Aedes vexans*, 2 aggressive biting species, have been identified in tire tracks and areas of pooled water left by inadequate grading. To aid mosquito control, mosquitofish (*Gambusia affinis*) were stocked in all wetlands and martin houses were constructed at some sites. Based on qualitative observations, it has been suggested that martins may not be very effective in mosquito control because of their affinity for dragonflies, which consume a greater number of mosquitos, including larvae (Tennessen 1990). The use of bats for mosquito control (Tuttle 1988) is also being investigated at the TVA wetlands with the installation of several bat houses.

Operation and Maintenance

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

Sampling and Analytical Techniques

The objective of sampling is to accurately represent the sampled material with a portion small enough to be conveniently handled and analyzed. Collection and handling of the sample must minimize changes in the sample prior to analysis. 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 analyzed according to standard methods (EPA, 1979).

Selection of Sampling Sites

Samples of acid seeps were collected from discrete boils or springs, if present. If there were no discrete points of groundwater discharge, then sample were obtained as follows. 1) For flat boggy areas, a site was located in the wet area high enough so surface water would not flow into an excavation large enough to obtain a sample. The hole was allowed to fill with seepage and, prior to sampling, the water level lowered to just above the point where seepage appeared to be entering. The hole was then allowed to refill and the water clarify. The sample was then collectedwithout stirring up sediments. 2) For seeps with very low flows on dike faces, highwalls, etc., a site was located up-gradient of the seep area on the dike, a hole was excavated down to the seepage, and the sample obtained as above. (EPA, 1985). Effluent monitoring was performed several meters downstream of the final spillway so that any dike leakage was included in the sample.

Water Sample Collection and Analytical Techniques

The objective of sample collection techniques was to minimize aeration and carbon dioxide loss before analysis. Sample bottles were filled from a plastic tube that was been pushed up-gradient into the seep, or the bottle was gently tilted into the flow (USGS, 1977). For seeps with very low flows, the bottle was lowered into the collection pit described above or a peristaltic pump was used to draw the sample (EPA, 1985). For the analyses that required extra attention to gas exchange, a polyethylene syringe of appropriate volume was used for sample collection and for short transport. The syringe tip was placed directly in the seep flow to draw an unaerated sample. All undosed sampling containers were rinsed three times with sample prior to the actual sample (APHA, 1989).

Total metals samples were collected in 500 ml acid-rinsed polyethylene bottles, predosed with 5 ml of 1+1 HNO_3, usually by tilting the bottle gently into the seep (APHA, 1989). Care wastaken to not overfill the bottle. The sample was then placed on ice and transported to the Chattanooga Environmental Chemistry Laboratory for analyses. Total metals samples were taken from the field containers, 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.

Dissolved metals samples were collected in one-liter plastic containers (cubitainers) by the same method described for total metals, and either filtered immediately after collection, or by carefully expelling air from the cubitainer, storing on ice, and then transporting a short distance to a field lab for filtration. The sample was vacuum filtered through a 0.45 micron cellulose ester membrane filter and poured into a 125 ml acid-rinsed polyethylene bottle predosed with 0.5 ml of 1+1 HNO_3 (APHA, 1989). The sample was then transported on ice to the lab for analysis. Samples are analyzed as received in the lab with standards for acid matrix by atomic emission or atomic absorption.

Ferrous iron samples were collected in 250 ml acid-rinsed glass bottles that were predosed with 5 ml of concentrated HCl. The technique is the same as described for total metals, with particular attention to preventing aeration (APHA, 1989). These samples were stored on ice and transportedto a lab for analysis by atomic emission or atomic absorption.

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 (APHA, 1989). Samples were filtered through glass fiber filter, dried at 102 to 105°C with the difference of weight retained on filter and reported as TSS.

Sulfate samples required a one-liter cubitainer and were handled the same as the TSS samples. Sulfate samples were determined by Automated Methyl Thymal Blue (MTB) Method. First samples were passed through a column to remove metal ions then reacted with an alcohol solution of barium chloride and methyl-thymal blue to form barium sulfate. The pH is then raised to 12.5-13.0 to react with MTB. The uncomplexed MTB is proportional to the sulfate concentration.

Acidity was field analyzed by two procedures, potentiometric titration curve and hot peroxide. Two samples were collected in 100 ml syringes, one being titrated electrometrically (Orion, Model 399A) with NaOH in 0.5 ml increments to check the equivalence point and determine normal acidity. The other sample was analyzed by the hot peroxide method to determine acidity after oxidation and hydrolysis of reduced metals (APHA, 1989). Comparison of these two acidity values gave a field check for appreciable amounts of acidity due to reducedmetals and/or levels of carbonic acid as carbon dioxide.

Alkalinity was field analyzed by collecting a sample with a 100 ml syringe and titrating electrometrically (Orion, Model 399A) with H_2SO_4 in 0.5 ml increments. This procedure was followed to check the equivalence point and determine the alkalinity (APHA, 1989).

Field analysis of the pH was performed by collecting the sample in a one-liter cubitainer, storing on ice, and transporting to a field lab for electrometric determination (Orion, Model 399A). In situ analyses were often made using a Hydrolab Model Surveyor II.

The Hydrolab was also used for in situ pH, DO, ORP, temperature, and conductivity analyses. These analyses were performed by lowering the instrument probes carefully into the seepage collection hole or a large sample container and recording the readings.

Results

A summary of characteristics and water quality parameters for TVA's 13 constructed wetlands is presented in Table 1. Significant water quality improvement has occurred at all of the wetlands. Nine systems have produced discharges that consistently meet NPDES discharge limitations (pH=6 - 9 s.u.; Fe < 3.0 mg/l; Mn < 2.0 mg/l; TSS < 35.0 mg/l) with no chemical treatment. Where regulatorylimits 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.

Figures 2-4 show inflow/outflow data for Fe, Mn, and pH at the 12 operational wetlands. Data for WCF5 was not available. Ten of the 12 operating wetlands produce discharges in compliance with total Fe limitations (i.e., < 3.0 mg/l). 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 the very low Fe inflow (0.7 mg/l) at the COF wetlands; this data may be a result of sampling and analysis techniques whose standard error is greater than the concentrations being measured, or may be related to 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 is less efficient (51 %) at KIF, where Fe loading exceeds 41 GDM. 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 obvious relationship in TVA's wetlands between Fe removal and influent alkalinity (Brodie et al 1991), Fe removal and wetlands size, or Fe removal and hydraulic loading. However, preliminary results at a TVA wetlands research facility suggest a correlation between Fe and Mn removal and hydraulic loading (Tomljanovich et al 1991).

Figure 3 shows total Mn loading and removal in the 12 TVA wetlands. Data for WCF5 is not available. Nine of the 12 operating wetlands produce discharges in compliance with total Mn limitations (i.e., < 2.0 mg/l, if regulated). 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 obvious relationship in TVA's wetlands between Mn removal and wetlands size, or Mn removal and hydraulic loading. Figure 4 shows a relationship between Mn removal and influent alkalinity and acidity concentrations (Brodie et al 1991). 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/l 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 may reflect Mn co-precipitation on Fe-oxides at circum-neutral pH as a likely mechanism of Mn removal (Faulkner and Richardson 1990).

Figure 5 shows influent/effluent pH for the 12 operating wetlands. Nine of the 12 systems increase or maintain inflow pH to produce discharges in compliance for pH (i.e., 6.0 - 9.0 s.u.). Three systems cause pH decreases due to Fe hydrolysis; these systems are being modified with anoxic limestone drains (Brodie et al 1991).

All of the wetlands produce discharges in compliance with total suspended solids (TSS) limitations (i.e., < 35 mg/l).

Impoundment 1

Impoundment 1 (IMP1), 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, IMP1 has generally produced compliance-quality effluent. Figure 6 shows average water quality data during the period July 1985 to November 1990 for the wetlands inflow and the discharges from each of the 4 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 % of the time. Figure 7 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 IMP 1 average discharge concentration of Mn. Similar, but less drastic, increases in Mn concentrations were noted in the summers of 1986 and 1987. When these anomalieswere compared to rainfall records and wetlands flow, no correlations were apparent. Other wetlands (e.g., 950NE and RT2) 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, degree of electron acceptors, redox conditions, nutrient and/or carbon availability, or photosensitivity of Mn-oxidizing bacteria (Sunda and Huntsman 1988; Hem 1981).

Figures 7 and 8 show the amounts of Fe and Mn removed for one 13-month period at IMP1. These data show that the wetlands consistently removes about 1.25 GDM Fe year-round. Mn removal is seasonal averaging about 0.14 GDM.

IMP1 is one of 2 constructed wetlands receiving inflow total Fe concentrations exceeding 50 mg/l that has successfully produced compliance-quality discharges without chemical treatment. Other wetlands receiving greater than 50 mg/l total Fe (see Table 1) have been troubled with low pH, high proton 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 200 mg/l and may represent the oldest, working anoxic limestone drain (Brodie and Garvich 1991). The 3 other high-Fe wetlands had influent alkalinity ranging from 0 to 26 mg/l with high acidity. Further investigations into the IMP1 characteristics showed that the leaking coal slurry impoundment dike was constructed in 1974 over an existing limestone coal mine haul road. Historically, local limestone has been quarried from the Monteagle Formation, an oolitic, high-$CaCO_3$ limestone. Apparently, this road, and perhaps some carbonate riprap emplaced in the early 1980s on the dike outslope, is the source of the IMP1 influent alkalinity. Recent developments suggest that buried limestone-backfilled trenches, if maintained in an anaerobic state, can passively increase alkalinity in wetlands influents to sufficiently buffer the water and prevent drastic pH decreases due to Fe hydrolysis (Turner and McCoy 1990; Brodie et al, 1991). Relationships in TVA's wetlands among influent alkalinity, effluent pH, Fe, and Mn confirm that wetlands treatment is enhanced by higher influent alkalinity.

Stability problems at IMP1 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 IMP1: broadleaf cattail (*Typha latifolia*), wool grass (*Scirpus cyperinus*), rush (*Juncus effusus*), scouring rush (*Equisetum hyemale*), and squarestem spikerush (*Eleocharis quadrangulata*). Over 60 vegetative species have been identified in IMP 1, dominated by *Typha latifolia*, *Scirpus cyperinus*, *Juncus effusus*, *Eleocharis quadrangulata*, and rice cutgrass (*Leersia oryzoides*).

Total cost of the IMP1 wetlands was $43,000 (1985 dollars). Annual costs have been about $13,000 due to repairs on the prototype design and extensive monitoring.

Impoundment 4

Impoundment 4 (IMP4), also at the Fabius plant site, was built in fall 1985 to treat acid seepage emanating from upstream plant process water recirculation ponds. These ponds were reclaimed in 1986 and the inflow to IMP4 essentially ceased due to the reclamation and drought conditions from June 1986 to December 1987.

IMP4 never produced compliance-quality effluent from November 1985 to May 1990 due to the low alkalinity and pH problems from high Fe hydrolysis. Therefore, the discharge has required chemical treatment with sodium hydroxide (NaOH) since initial operation. Chemical addition took place in the third wetlands cell. However, large rainfall events flushed low pH water from the upper 2 cells and lowered the discharge pH to below permit limitations. Chemical treatment of all cells was then implemented and a 0.1 ha retention pond was constructed in 1988 below the existing wetlands to facilitate chemical treatment.

In April 1990, an anoxic limestone drain was installed upstream from the wetlands to pretreat the inflow by increasing the alkalinity. Such buffering capacity in the inflow has prevented pH drop and neutralized acidity, thereby enhancing the overall treatment efficiency of IMP4 and allowing the cessation of chemical treatment since May 1990 (Brodie et al 1990, 1991). Total cost of the wetlands was $28,000 (1985 dollars) with $32,000 average annual costs through May 1990, primarily for chemical treatment. The anoxic drain cost $19,000; thus it paid for itself in about 8 months. Thirty-five vegetative species in IMP 4 are dominated by Eleocharis quadrangulata, Juncus effusus, Scirpus cyperinus, and Typha latifolia. The original planting of IMP4 took place in November 1986, but few plants survived through winter and the wetlands was replanted the following July.

950-1 and 2

The 950-1 and 950-2 wetlands was a 2-cell sedimentation basin treating acid mine drainage from the reclaimed TVA Fabius 950 coal mine in Jackson County, Alabama. The upstream cell naturally developed into a cattail (Typha spp.) marsh that has expanded into the lower cell. Treatment with NaOH was required from 1976 to 1984. The discharge was released from NPDES permit monitoring requirements in 1987.

Continued quarterly influent/effluent monitoring has shown that the 950 discharge has remained within regulatory limitations (see Table 1).

Impoundment 2

Impoundment 2 (IMP2) is a series of constructed wetlands intermediate in a 138 ha drainage basin. It receives high flows of acid drainage from non-TVA abandoned mine land, acid pumpage from the slurry lakes, and drainage from the coarse refuse (gob) disposal area at the Fabius plant site. Effluent from the wetlands is treated with NaOH and discharged into a 1.1 ha retention pond. The system receives the lowest pH inflow of all of the TVA wetlands (< 3.5 s.u.) and is still removing Fe from 40 mg/l to about 3 mg/l (4.9 GDM). Thirty-seven vegetative species are present in the IMP2 wetlands and are dominated by cattail (Typha spp.) and squarestem spikerush (Eleocharis quadrangulata). Future measures to improve this wetlands system include expansion of the wetlands and construction of an anoxic drain, in addition to reclamation of the gob pile and slurry lakes.

Widows Creek 005

Widows Creek 005 (WCF5) is located at TVA's Widows Creek Fossil Plant and treats acid drainage from an active ash pond dike and runoff from the limestone storage silo area. The ponds were built in 1987 and became devoid of vegetation due to extreme water depth and muskrats. The system was replanted in July 1990 and the water level reduced to less than 0.5 m. The inner slopes of the dikes were lined in 1990 with metal fencing to discourage muskrat burrowing and habitation.

<u>Widows Creek 006</u>

Widows Creek 006 (WCF6, formerly known as WIF 018), located at TVA's Widows Creek Fossil Plant in Jackson County, Alabama, treats high flows of acid seepage from an abandoned coal ash disposal area. High-iron, zero-alkalinity inflows result in high-acid production and low-pH values in the wetlands (see Table 1). The wetlands has always required chemical treatment to achieve compliance discharges. An anoxic drain is being considered for this system.

Thirty-two vegetative species in the wetlands are dominated by <u>Eleocharis quadrangulata</u>, <u>Juncus effusus</u>, <u>Scirpus cyperinus</u>, and <u>Typha spp</u>. In August 1986, an infestation of cattail armyworms (<u>Simyra henrici</u>) significantly damaged 60 to 80 percent of the cattails in WIF6 (Snoddy et al 1989). The infestation was attributed to the rapid development and the monocultural nature of the cattails at WCF6 and was controlled with the insecticide Lorsban.

<u>Widows Creek 019</u>

Widows Creek 019 (WCF19, formerly known as WIF 019) treated acid seepage from abandoned and active coal ash disposal areas. Widows Creek Fossil Plant's operational needs at this site resulted in flooding the wetlands and installing a facility to pump water to an existing ash pond for treatment.

<u>Impoundment 3</u>

Impoundment 3 (IMP3) is located at the TVA 950 Coal Mine and treats acid mine drainage. It was constructed to replace a chemical treatment system which operated from 1976 to 1986 at a cost of $300,000. The wetlands was built at a cost of $40,000. When compared to previous annual operating costs of nearly $25,000 and the inability to maintain compliance even with chemical treatment, the cost and environmental benefits of this wetlands are obvious.

In August 1987, a muskrat burrowed into cell 2 dike of the wetlands which resulted in catastrophic failure of the dike. The dike was repaired and the inner slopes of all dikes were lined with chain link fence and coarse riprap to prevent muskrat burrowing.

IMP3 has always produced compliance-quality discharges. The ecological recovery of Kash Creek, the IMP3 receiving stream that was severely impacted by acid mine drainage and NaOH treatment, was documented in June 1986 and June 1987 macroinvertebrate surveys. Only 2 taxa were identified in the 1986 pre-wetlands survey. Nineteen taxa were identified in the 1987 survey in Kash Creek and 31 taxa were found in the constructed wetlands. Thirty species are present in the wetlands dominated by <u>Scirpus cyperinus</u>, and <u>Typha spp</u>.

IMP3 was released from NPDES monitoring requirements in August 1989. This action was the first release of a TVA constructed wetlands.

Rocky Top 2

Rocky Top 2 (RT2) is located at TVA's reclaimed Fabius Rocky Top coal mine in Jackson County, Alabama. Inflow is acid mine drainage. This wetlands consists of a .25 ha deep pond followed by 2 wetlands cells constructed to replace a chemical treatment system. Total Fe and total Mn effluent concentrations for the period October 1987 to July 1989 show seasonal variations, similar to IMP1, in metals removal efficiencies that have resulted in slightly elevated Fe and Mn concentrations during the late winter and spring months. The compliance record at this site allowed its release from NPDES monitoring in June 1990. Thirty-six vegetative species are present in the wetlands dominated by *Scirpus cyperinus* and *Juncus effusus*.

950NE

The 950NE is located adjacent to the TVA 950 coal mine and treats acid mine drainage from about 32 ha of reclaimed area. As found in data for IMP1 and RT2, there is seasonal variation in metals removal efficiencies at 950NE with elevated Fe and Mn concentrations in the winter months. This impoundment, however, has produced compliance-quality discharges since initial operation, and release from NPDES monitoring requirements was approved in March 1990.

Of special concern at 950NE were beavers. The spillways at 950NE consisted of wide, trapezoidal, coarse riprapped channels. In 1988, beavers began damming 2 of the spillways using mud and cattails. After unsuccessful attempts to eliminate them, the spillways were fitted with culverts with upstream 90° elbows to prevent water level increases in the cell due to beaver activity. This action has not been entirely successful and other control methods are being tested at this and other sites. Thirty-one vegetative species in the wetlands are dominated by *Scirpus cyperinus* and *Typha spp*.

Dead Lady Lake

The Dead Lady Lake Wetlands (DLL) is located at the TVA 950 Coal Mine and treats acid mine drainage. The wetlands was completed in May 1990. Preliminary results indicate that this system is producing compliance quality effluent.

Kingston 006

Kingston 006 (KIF) is located at TVA's Kingston Fossil Plant in Roane County, Tennessee. It was constructed to treat high flows of acid seepage from a coal ash disposal area. About 20 cm of high-calcium, minus-16 mesh limestone covered with about 30 cm of spent mushroom compost for vegetative substrate was included in the final cell of the wetlands system in an attempt to elevate pH. No significant effects on the effluent were noted due to the limestone bed. KIF is another high-Fe, low alkalinity system that has resulted in extremely low pH (2.9 s.u.). Effluent from the third cell has been pumped to the active ash pond for treatment while the system is under development. Remedial plans are being implemented for the system which include the use of bactericides (Sanda 1989) and an anoxic drain and oxidation basin, in conjunction with partial reclamation of the ash disposal areas. Twenty-three vegetative species are dominated by a sedge (*Cyperus erythrorhyzos*) and *Typha spp*.

Colbert 013

Colbert 013 (COF) is located at TVA's Colbert Fossil Plant in Colbert County, Alabama. It treats acid drainage from an indefinite source near an active ash disposal area. The COF wetlands is unique in that the influent water quality is characterized by very low Fe and higher Mn (see Table 1). Total Mn to total Fe ratios in non-chemically treated TVA wetlands influents range from 0.03 to 0.81, with the exception of COF which has a Mn/Fe ratio of 7.60. TVA's wetlands have Mn removal efficiencies ranging from zero (in low-pH systems) to 96 %. COF has a Mn removal efficiency of 34 % but is a relatively high-pH system. TVA is currently investigating the Mn removal efficiency at COF which could be related to absence or inhibition of Mn-oxidizing bacteria in the system or lack of Fe-Mn coprecipitation due to the low influent Fe concentration (0.7 mg/l). Initially, only pH was beneficially affected within the wetlands. Because Mn levels exceeded permit limitations, NaOH treatment was required in the third and fourth cells since 1987. Removal of Mn limitations at this site in 1990 has allowed cessation of NaOH treatment. A pilot study is now underway aimed at improving Mn removal at the COF wetlands including evaluating the use of rock filters to biologically remove manganese (Gordon and Burr 1989). The wetlands is dominated by *Typha spp*. and *Scirpus cyperinus*.

Summary and Conclusions

TVA has constructed 13 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, 4 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/l), relatively high total Mn to total Fe ratios in the influent (average Mn/Fe = 0.44), significant inflow alkalinity (35 - 300 mg/l), and variable Fe loading (.03 - 6.13 GDM).

Five systems have experienced high proton-acidity production and low pH within the wetlands due to Fe hydrolysis. Four of these systems are associated with high influent Fe concentrations (40-170 mg/l), 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, KIF, is currently being modified with an anoxic limestone drain.

One system (COF) that has experienced very little metals removal is associated with low Fe (0.7 mg/l) and higher Mn (5.3 mg/l). The performance of this wetlands may be related to absence or inhibition of Mn-oxidizing bacteria or lack of Fe-Mn coprecipitation.

Fe and Mn removal efficiencies and pH improvement in the TVA wetlands show no obvious relationship to calculated treatment areas for total Mn or flow. This, in part, is probably due to the effect of Fe hydrolysis and H^+ production 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. These numbers may represent crude upper limit sizing criteria.

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 2 or 3 cell constructed wetlands for Mn and further Fe removal. Adjustment of pH, if necessary, may take place in a post-wetlands system incorporating an alkaline bed (Brodie et al 1991). 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)				Effluent Water Parameters (mg/L or L/min)						Loading g/day/m^2		l/day/m^2
												Flow				
				pH	Fe	Mn	TSS	pH	Fe	Mn	NFR	Ave	Max	Fe	Mn	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	5.5	170.0	4.4	40.0	2.9	82.5	4.6	-	1574	2271	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

*Also receives pumpage from slurry lake up to 4800 l/min.

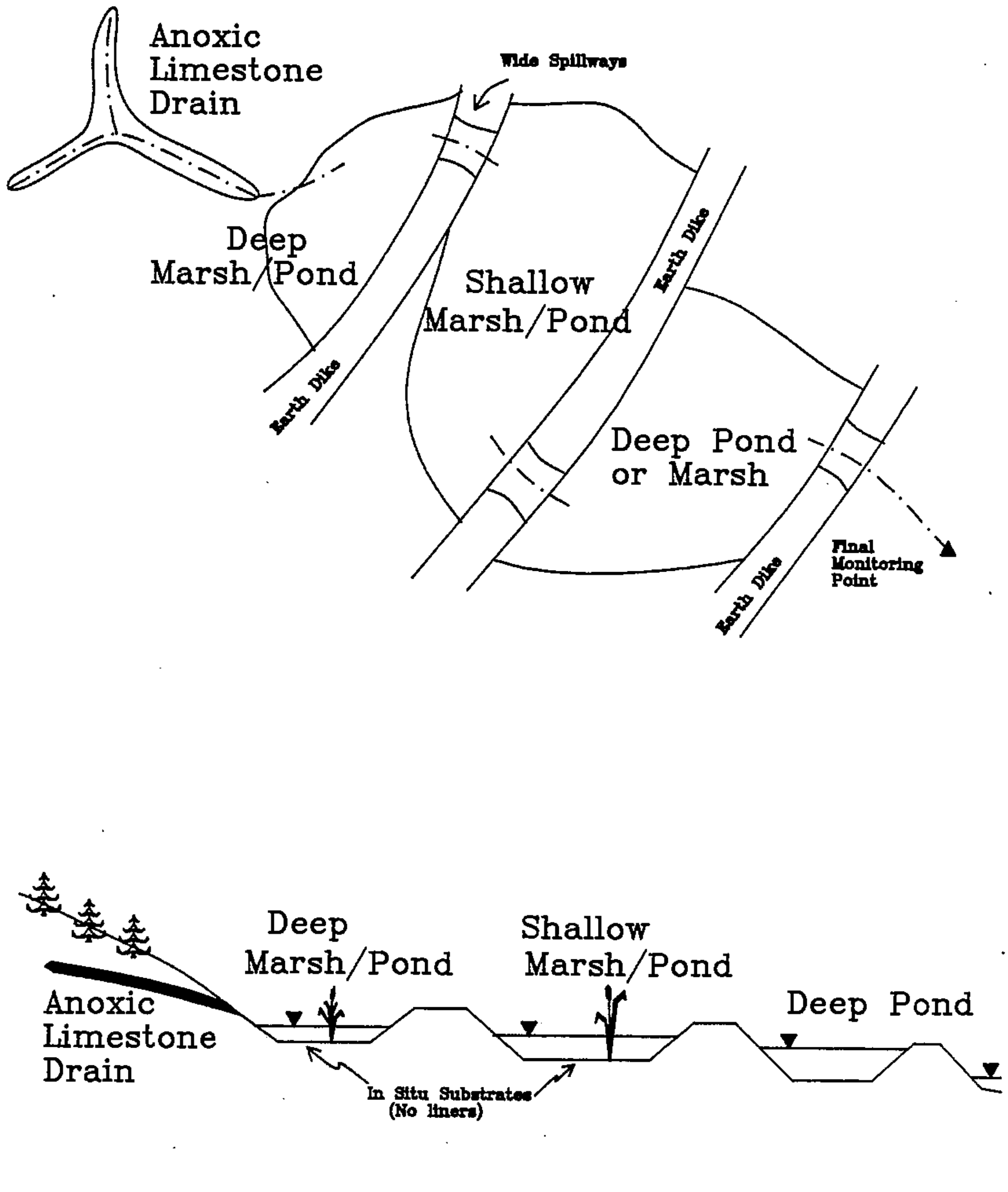

Figure 1. Schematic of Typical Staged, Aerobic Constructed Wetlands

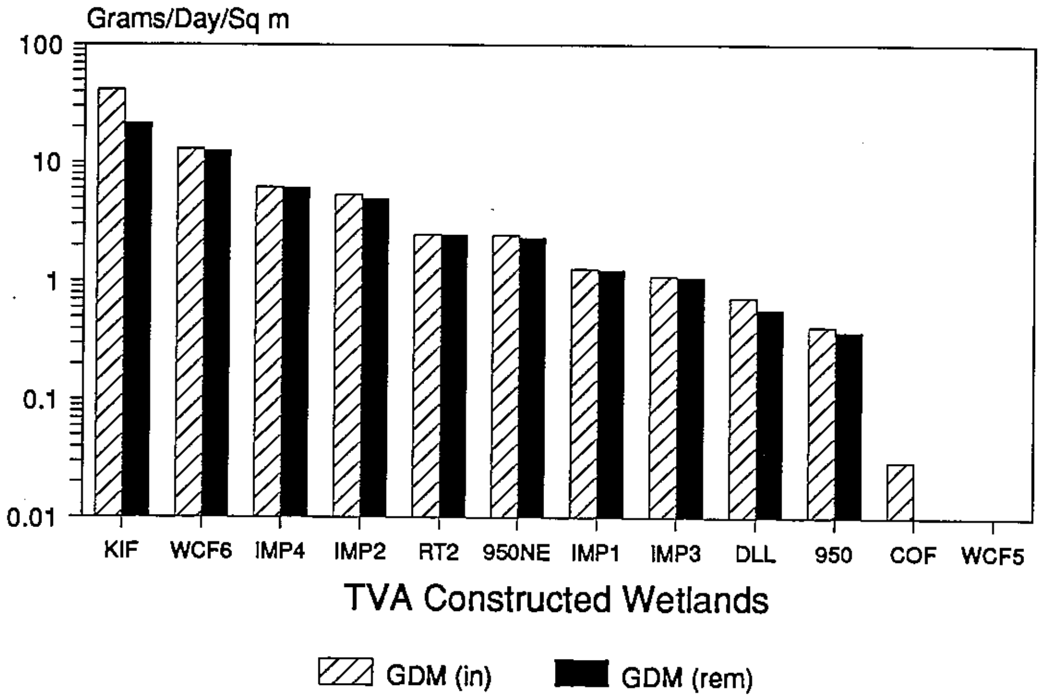

Figure 2. Fe Loading and Removal in TVA Wetlands

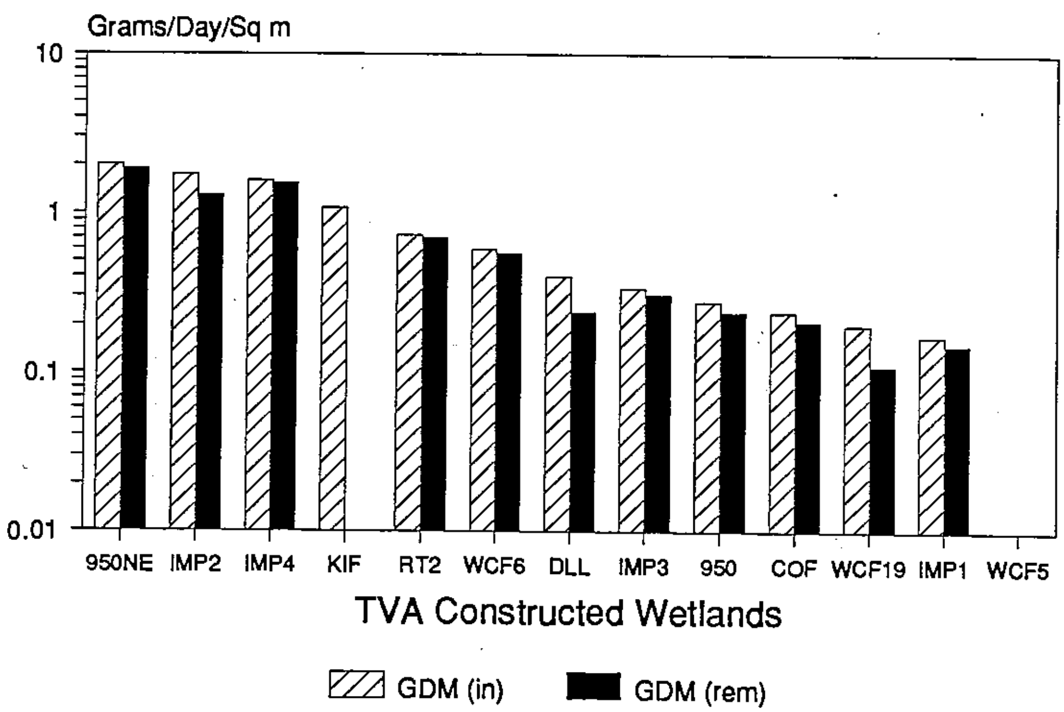

Figure 3. Mn Loading and Removal in TVA Wetlands

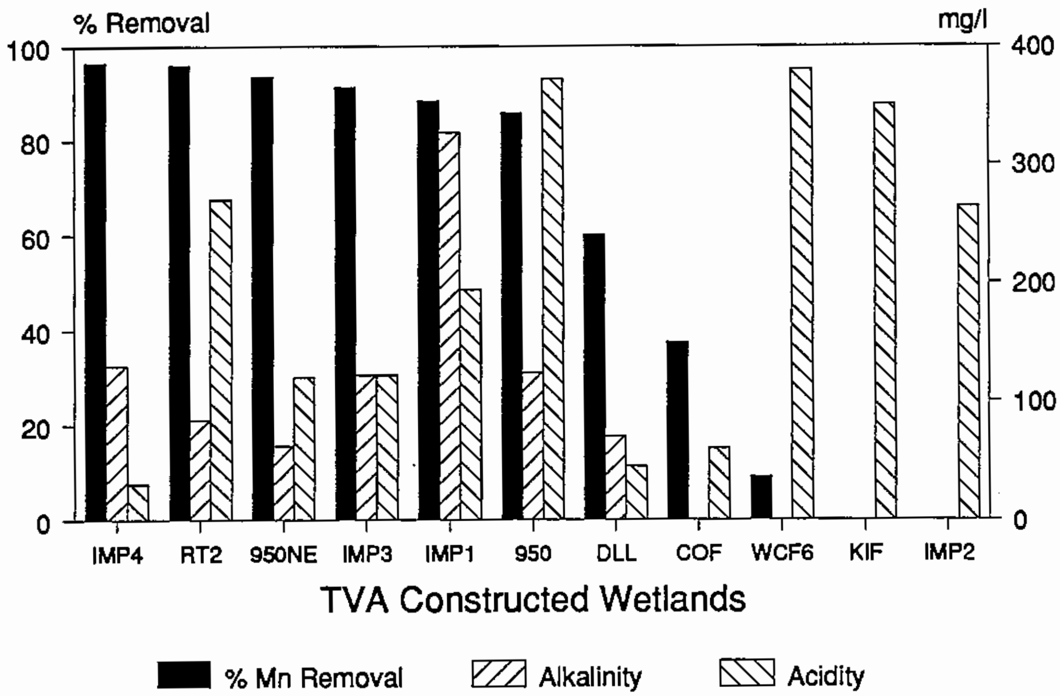

Figure 4. Mn Removal Related to Alkalinity and Acidity

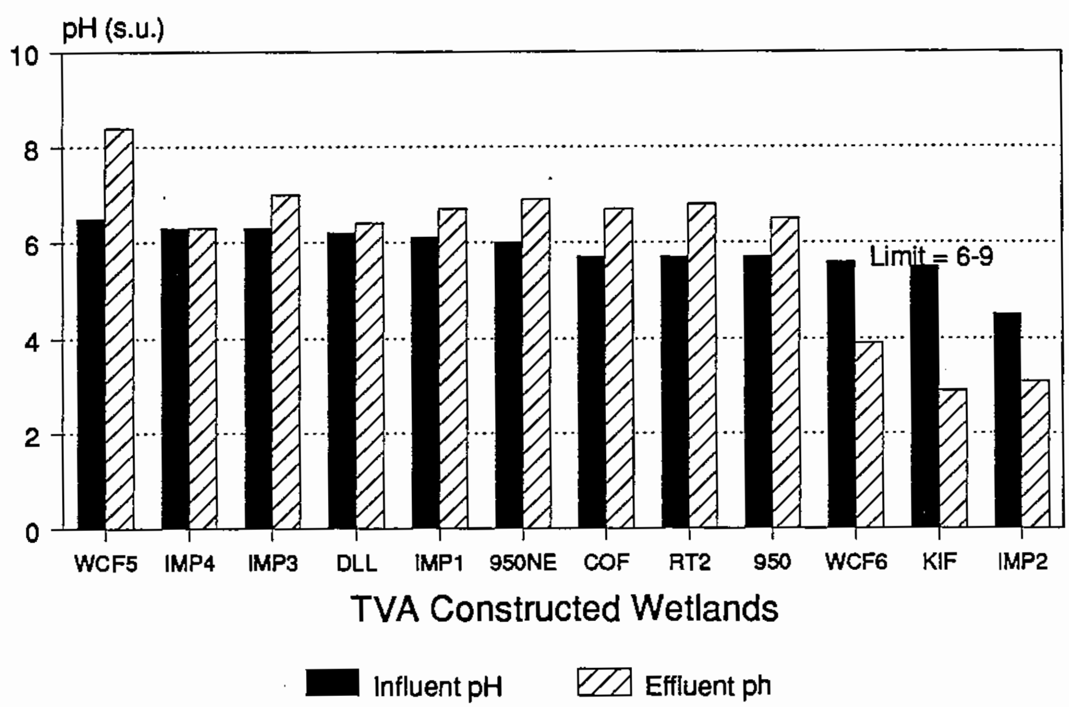

Figure 5. Influent and Effluent pH in TVA Wetlands

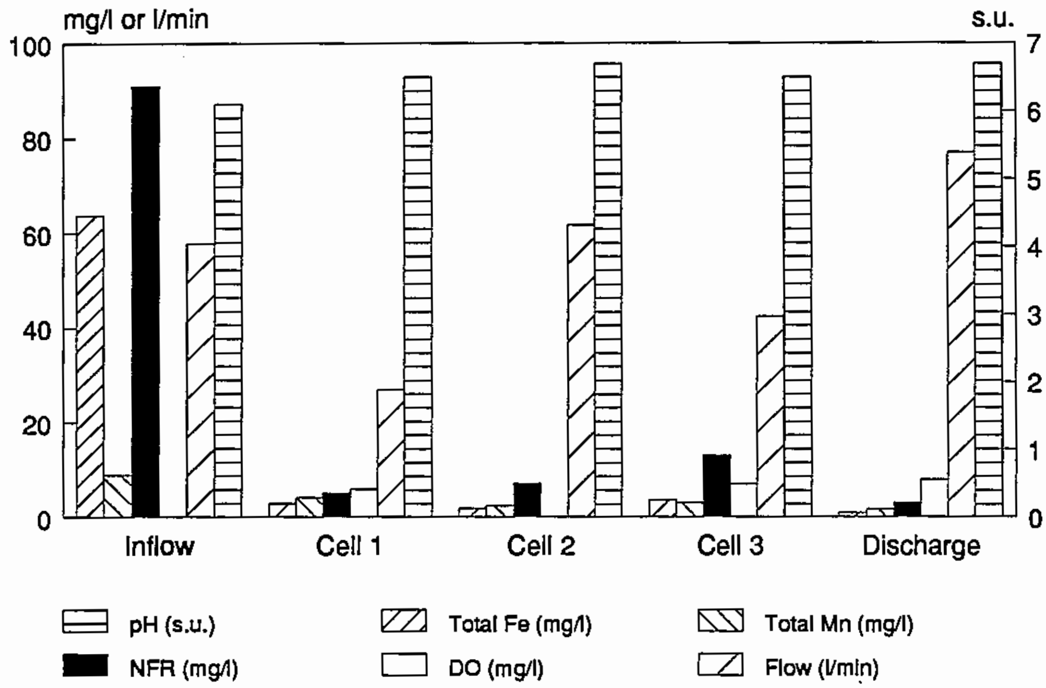

Figure 6. Fabius IMP1 Wetlands Average Water Quality Data

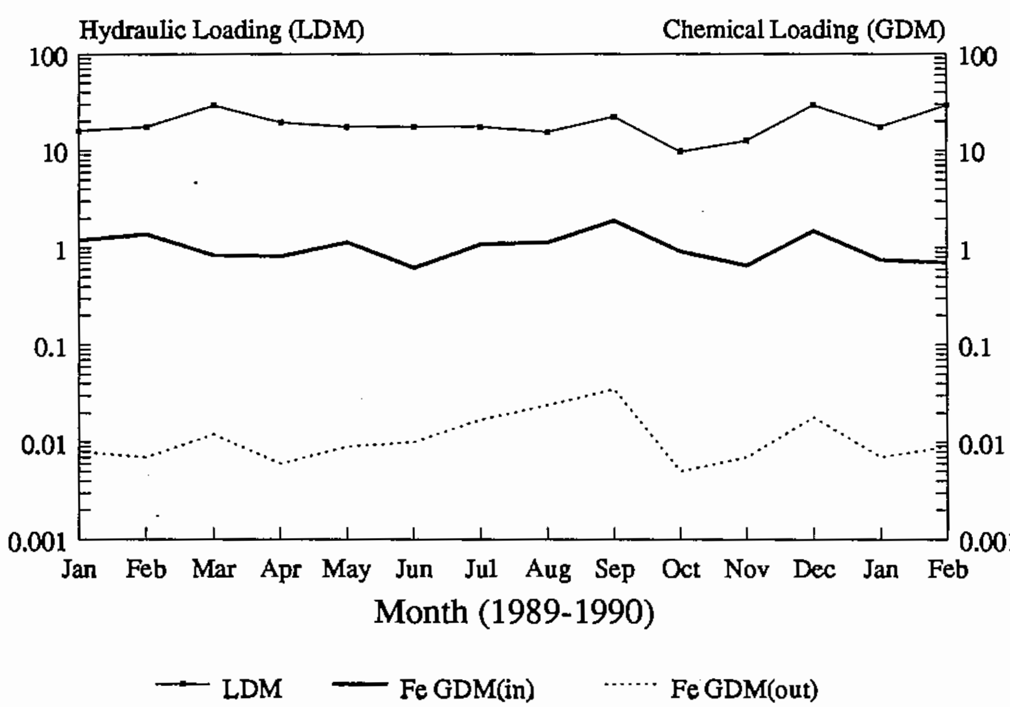

Figure 7. Fabius IMP1 Wetlands Fe Loading and Removal

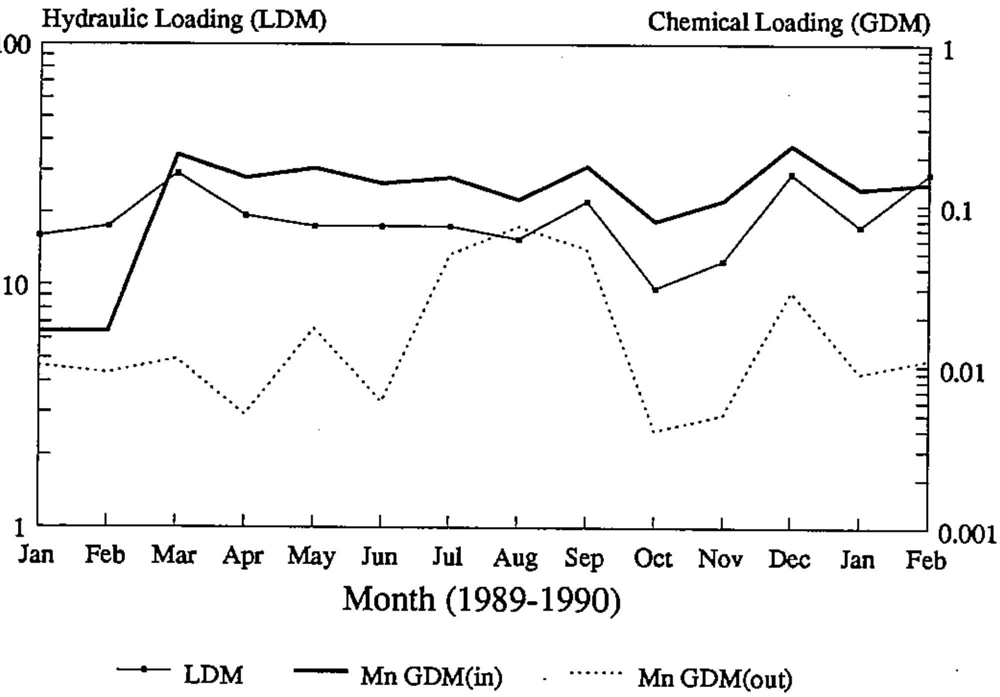

Figure 8. Fabius IMP1 Wetlands Mn Loading and Removal

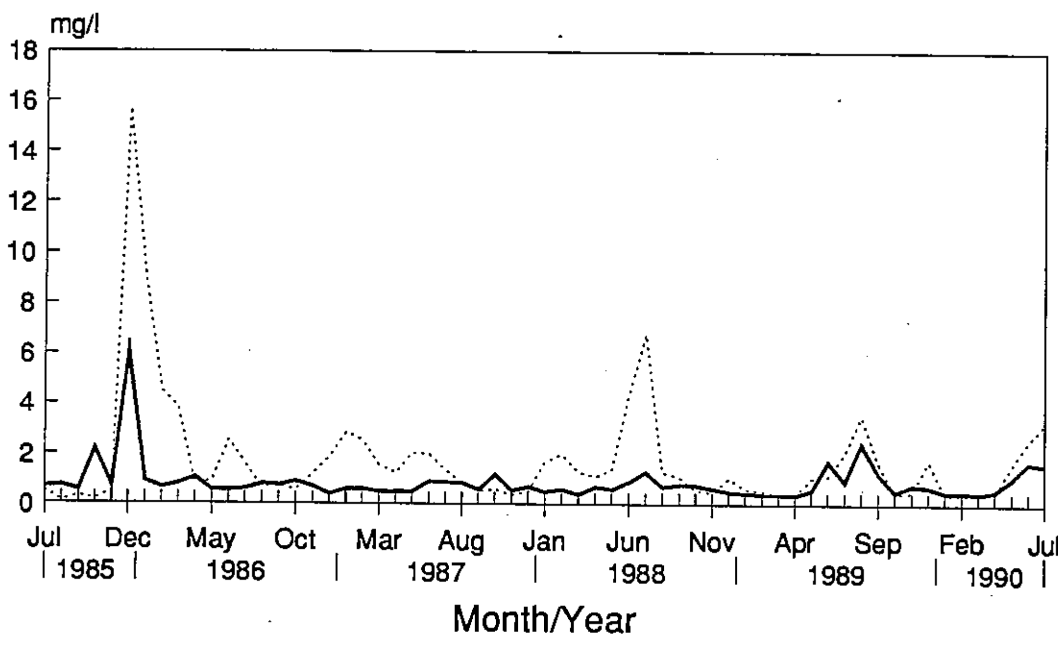

Figure 9. Fabius IMP1 Wetlands Effluent Fe & Mn Data