Wetland Design for Mining Operations

Section II

STAGED, AEROBIC, WETLANDS-BASED ACID DRAINAGE TREATMENT SYSTEMS

DESIGN, CONSTRUCTION, AND OPERATION

Gregory A. Brodie, Environmental Engineer

Tennessee Valley Authority
Fossil & Hydro Power
1101 Market Street
Chattanooga, Tennessee
615-751-2064

Table of Contents

INTRODUCTION

Staged, aerobic, constructed wetlands-based systems offer a potential low-cost, natural, low-maintenance, and long-term alternative to conventional treatment of acid drainage (Brodie, 1992a, Appendix 1). Guidelines for design and construction of treatment wetlands exist but, although useful for general planning purposes, should not be considered comprehensive due to the rapidly evolving constructed wetlands technology (Brodie, 1989, 1990, 1991c; Brodie et al, 1988; Hammer, 1989; Karathanasis, 1991; Kleinmann et al, 1990; Pesavento, 1984; Reed et al, 1988; U.S. EPA, 1985; Wildeman et al, 1991; WPCF, 1990). This workshop is designed to present current guidelines on the processes of preliminary considerations, design, operation, and maintenance of staged, aerobic constructed wetlands for treating acid drainage. The design concepts discussed are therefore primarily oriented to acid water treatment and are probably not optimal for other types of wetlands construction on mined lands (e.g., mitigation wetlands). However, because the types of systems described in this report are efficient at removing suspended solids, the designs may be useful for managing small to moderate flows of stormwater.

Using wetlands for water pollution control began in Europe where research and applications involving wetlands and vegetative waste treatment date back to the early 1950's. In the U.S., experimental application of wastewater was tested in wetlands during the 1970's. However, treatment of acid drainage did not evolve from wastewater treatment but rather from water quality studies at sites where acid mine drainage was flowing into natural Sphagnum moss bogs.

The first of these studies, by a group at Wright State University, found Sphagnum recurvem growing in pH 2.5 water in Ohio's Powelson Wildlife Area. Iron, magnesium, sulfate, calcium and manganese all decreased while pH increased from 2.5 to 4-6 s.u. as the water flowed through the bog. A natural outcrop of limestone located downstream provided sufficient neutralization to raise the effluent pH to between 6 and 7 s.u. (Huntsman et al, 1978).

A similar study was conducted by a West Virginia University group at Tub Run Bog in northern West Virginia. They found that acid drainage flowing into the wetlands area rapidly improved in quality. In 20 - 50 meters, pH rose from 3.0 - 3.6 s.u. to 5.5 - 6.1 s.u., while only 10 - 20 meters of flow through the bog was needed to reduce sulfate concentrations from 210 - 275 mg/l to 5 - 15 mg/l and iron from 26 - 73 mg/l to less than 2 mg/l (Wieder et al, 1982).

WETLANDS PROCESSES

"Wetlands" is a generic term encompassing swamps, marshes, bogs, wet meadows, fens, etc. The term allows general discussion of at least two types, cattail marshes and peat moss bogs, which are dominated by plants that actually prefer slightly to moderately acidic water. These plants also tolerate levels of sulfate and various metals that would be toxic to most plant forms. Most important, these plants form the framework for a self-maintaining ecosystem that removes metals, mineral acidity, and sulfates.

Several physical, chemical, and biological processes contribute to changes of the chemistry of mine drainage as it flows through a constructed wetlands (Figure 1). The simplest mechanism is dilution. Wetlands are normally built on a hydrologically low site, and additional flows from surface drainage or non-target groundwater seeps are common. In some systems, major inflows of uncontaminated groundwater and storm runoff can cause changes in chemistry that might be mistakenly attributed to biological or chemical processes. Hedin (1992) has suggested a methodology using Mg concentrations as an adjustment factor which accounts for dilution effects in a constructed wetlands.

Probably the most important metal removing mechanisms in wetlands, as they are currently being constructed, are bacterially-catalyzed oxidation and hydrolysis reactions that cause dissolved iron to precipitate as insoluble iron, which is incorporated into the substrate. In one study of the metal chemistry of peat in a 10-month-old constructed wetlands, 93 percent of the accumulated iron and 27 percent of the manganese accumulation were in oxidized forms (Wieder et al, 1985). Other more recent studies substantiate Wieder's findings (Faulkner and Richardson, 1990; Tarutis and Unz, 1990). Iron oxidation and hydrolysis, however, is an acid-generating reaction which acts to lower pH. These reactions are summarized below (Stumm and Morgan, 1970).

(1) $FeS_2 + 7/2O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} = 2H^+$

(2) $Fe^{2+} + 1/4O_2 + H^+ = Fe^{3+} + 1/2H_2O$

(3) $Fe^{3+} + 3H_2O = Fe(OH)_3 + 3H^+$

(4) $FeS_2 + 14Fe^{3+} + 8H_2O = 15Fe^{2+} + 2SO_4^{2-} + 16H^+$

Note that these reactions are catalyzed by the bacterium Thiobacillus ferrooxidans.

Faulkner and Richardson (1990a) also suggest that Mn sorption to Fe oxides is a likely, long-term Mn removal mechanism. Successful Mn removal at wetlands receiving excess alkalinity from anoxic limestone drains may be attributed to Mn coprecipitation (Brodie, 1992a). Biological rock filters for Mn removal may also be appropriate(Gordon, 1989; Meehan, 1991).

Another potentially important mechanism is bacterial sulfate reduction, which occurs in the anaerobic organic substrate (Dvorak et al, 1991; Hedin et al, 1989; McIntire and Edenborn, 1990). Wetlands constructed with a composted organic substrate show high rates of biological activity and very significant rates of sulfide production. The sulfide ion reacts with metals to form an insoluble precipitate, which remains buried in the organic mass. More important, is the fact that this reactions series consumes acidity and acts to raise pH.

(5) $SO_4^{2-} + 2CH_2O = H_2S + 2HCO_3^-$

Hydrogen sulfide will, depending on the chemical environment, react with dissolved metals and precipitate as a polysulfide or iron sulfides (FeS, FeS_2).

POLLUTANT REMOVAL MECHANISMS
Aerobic Constructed Wetlands

MAJOR MECHANISMS

- Abiotic & Bacterially-Mediated Fe & Mn Oxidation
- Fe Hydrolysis
- Mn Sorption & Coprecipitation
- Carbonate Buffering
- Sulfate Reduction
- Burial/Diagenesis

MINOR MECHANISMS

-Dilution/Aeration & CO_2 Stripping
-Plant Uptake
-Absorption
-Chelation
-Mn-Carbonate Formation
-Cation Exchange
-Organic & Inorganic Complexing
-Algae & Fungi-Mediated Oxidation & Oxygenation

FIGURE 1

The neutralization aspect of sulfate reduction is, at present, more important than metal removal because oxidation and hydrolysis is a more efficient way to remove iron and dissolved iron can interfere with sulfide production (iron reduction precedes sulfate reduction). Therefore, biological treatment systems that incorporate sulfate reduction should designed to treat the water sequentially, so that most of the iron is removed aerobically before anaerobic processes predominate. Improvements in water quality may also result from the accumulation of metals in plants and in the organic substrate, and from microbially mediated reduction processes, and abiotic or microbially-catalyzed metal oxidation and hydrolysis reactions. Because wetlands have heterogeneous environmental conditions, these processes are intertwined.

Much of the original field and laboratory research with constructed wetlands focuses on the ability of plants to accumulate metals. Sphagnum has a well-established capability to accumulate iron (Burris et al, 1984; Gerber et al, 1985; Wenerick et al, 1988). However, except in low-flow, low-concentration situations ($Fe < 10$ mg/l), metal accumulation in Sphagnum reaches a toxic level within a single growing season (Spratt and Wieder, 1988). Thus, although many of the original constructed wetlands were built with Sphagnum, few remain operational. Typha is much more tolerant of mine drainage than Sphagnum, probably because it does not accumulate metals to high, toxic concentrations. Although Typha is the dominant source of productivity and living biomass in most constructed wetlands, its role as an iron sink is negligible and probably accounts for less than 1 percent of the annual inflow iron load.

Certain algae have recently received attention from wetlands builders and researchers because of observations that algal blooms are sometimes associated with decreased dissolved manganese concentrations. Some wetlands builders have attempted to enhance algal growth with periodic fertilization and by creating open water ponds in which competition with emergent plants for sunlight is reduced. Unfortunately, like removal of iron by plant accumulation, removal of manganese by algal activity is probably minor and only useful at low contaminant concentrations.

The organic substrates sometimes used in wetlands construction can remove metals from solution by adsorption, chelation and cation exchange processes. Detailed investigation of adsorption and chelation processes in peat systems has shown that metal-removal capacities are limited. In most constructed wetlands, these capacities would be exhausted with several months of exposure to acid drainage. In aerobic wetlands, the substrates do not contribute greatly to the pollutant removal processes except to the extent that they support the growth of aquatic vegetation.

PRELIMINARY CONSIDERATIONS

General

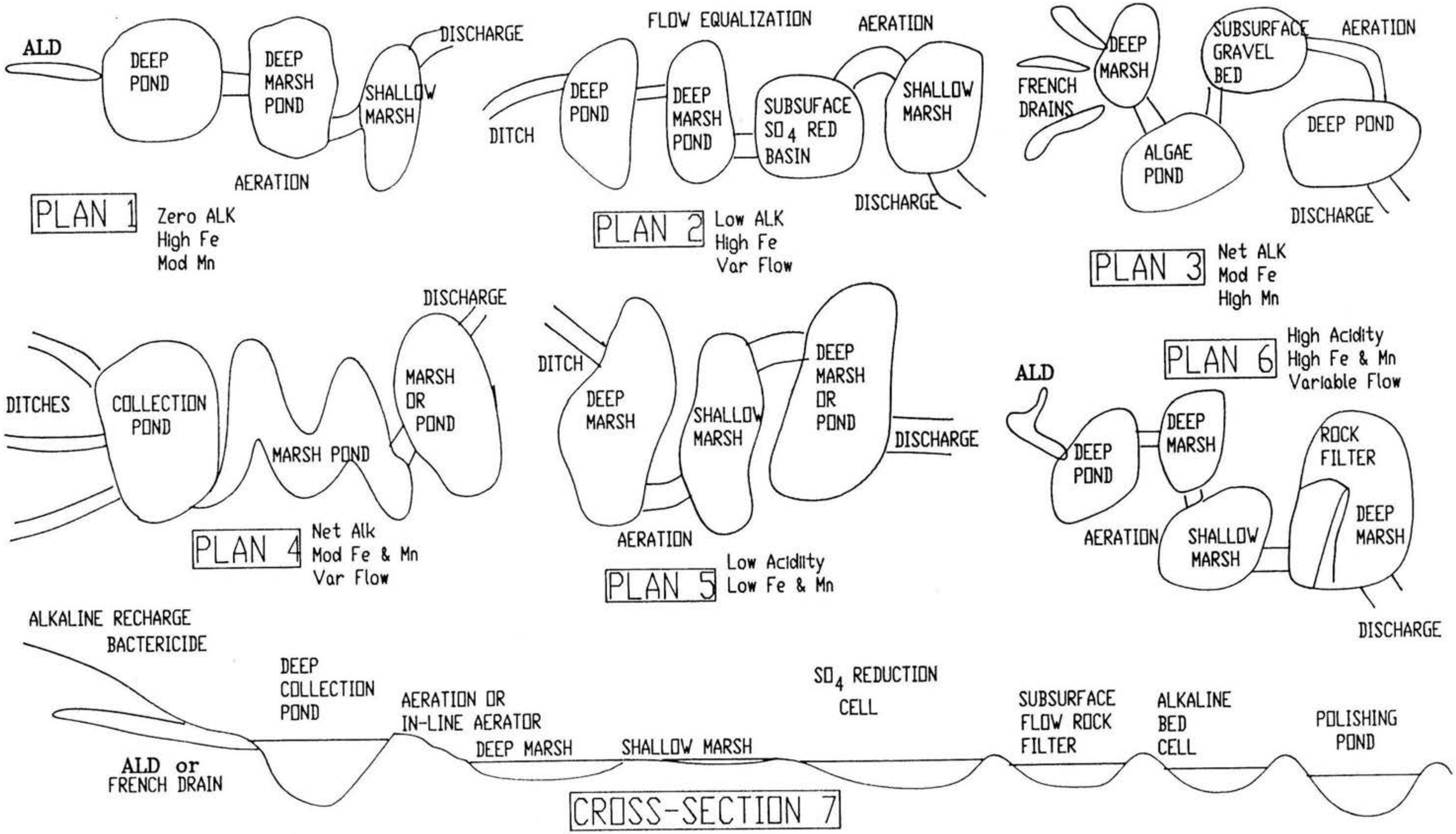
At the conception of a wetlands project, one should become familiar with existing and proposed regulations and guidelines regarding constructed wetlands. These requirements vary from state to state, but, in addition to potential local or regional requirements, could include the following.

Regulation/Requirement	Federal Law
Environmental Review	National Environmental Policy Act
National Pollutant Discharge Elimination System (NPDES) Permit	Clean Water Act
Mining/Reclamation Permit	Surface Mining Control and Reclamation Act
Air Quality/Construction Permit	Clean Air Act
Archaeological Survey	National Historic Preservation Act
Survey for Protected Species or Habitat	Endangered Species Act
Consideration of Floodplains and Existing Wetlands	Executive Orders 11998 (Floodplain Management) and 11990 (Protection of Wetlands)

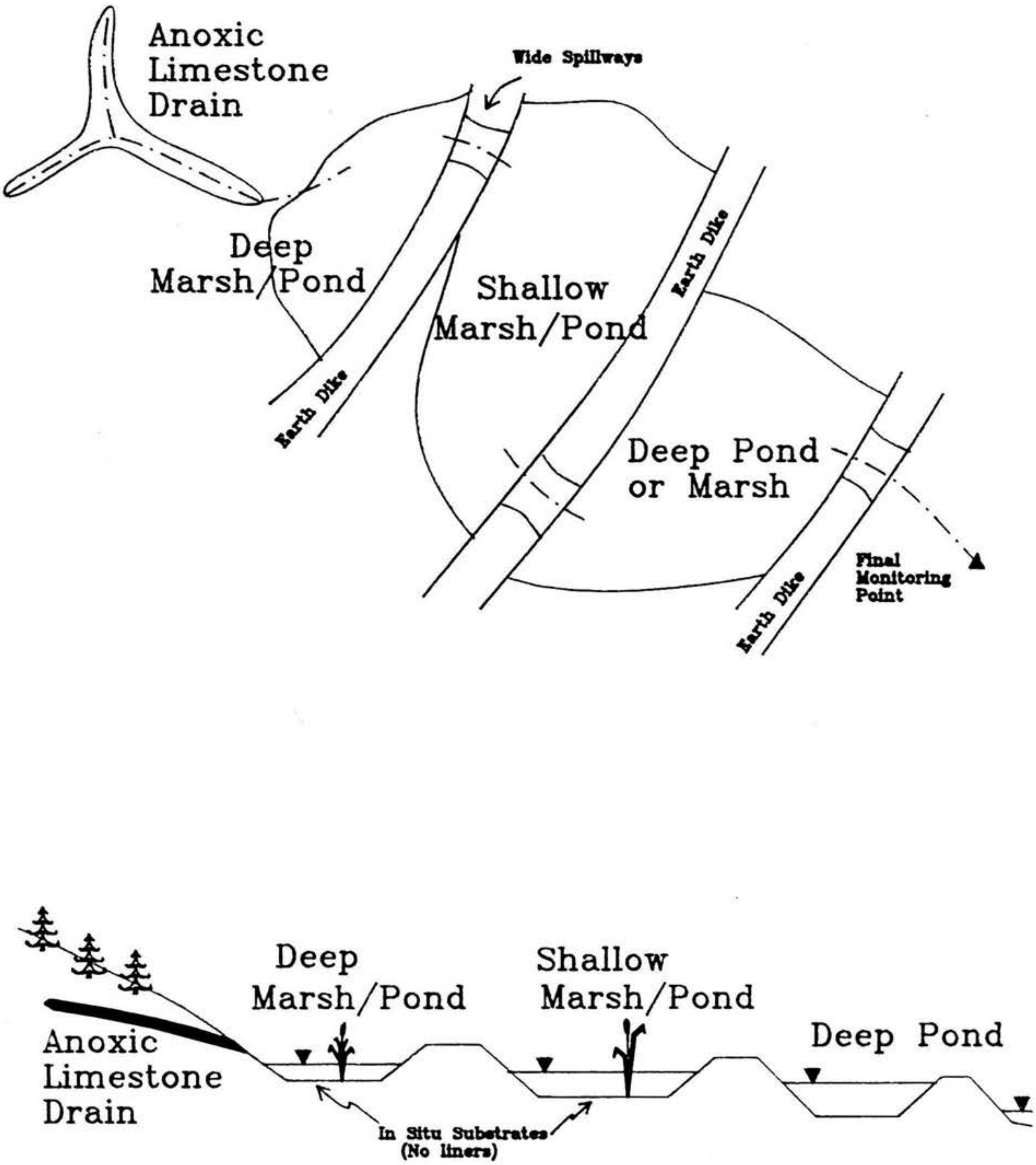
Site conditions that influence wetlands design and construction include hydrology, wastewater character, geology, soils, topography, access, land availability and use, and geotechnical attributes. Selection and evaluation of sites for constructed wetlands treatment systems has been detailed elsewhere (Brodie, 1988). It is recognized that siting a wetlands system is usually limited to the areas immediate to the acid water discharge, however, certain considerations should be adhered to for favorable results.

Hydrology

Surface and groundwater flow patterns, use, quantity, and chemistry should be determined sufficiently to properly design major hydraulically sensitive components of a wetlands (e.g., dikes, spillways, channels, retention basins). Maximum stormflow into a wetlands should be closely estimated because of the profound effects (scouring, flushing of sediments, overloading, structural failure) of surface runoff on a wetlands system. Conversely, periods of low or no flow should be determined. Acid inflows should be completely characterized chemically to determine the presence of major and hazardous constituents. Minimally, inflows to a proposed wetlands should be sampled and analyzed several times over the year for pH, dissolved oxygen, total and dissolved Fe, total manganese, aluminum, total sulfate, alkalinity, and acidity. A determination of the presence of toxic constituents (e.g., heavy metals, pesticides, organics) is recommended, especially if the source of the acid water is not well-defined or is a process waste (e.g., coal ash, gob). Nearby water wells, springs, or public water supplies should be sampled to document pre-wetlands water quality. Downstream water quality and biologic surveys may be useful in documenting stream recovery to support release from a permit.



ALD
DEEP POND
DEEP MARSH POND
SHALLOW MARSH
DISCHARGE
AERATION
PLAN 1
Zero ALK
High Fe
Mod Mn
FLOW EQUALIZATION
AERATION
DITCH
DEEP POND
DEEP MARSH POND
SUBSUFACE SO_4 RED BASIN
SHALLOW MARSH
DISCHARGE
PLAN 2
Low ALK
High Fe
Var Flow
DEEP MARSH
SUBSURFACE GRAVEL BED
AERATION
FRENCH DRAINS
ALGAE POND
DEEP POND
DISCHARGE
PLAN 3
Net ALK
Mod Fe
High Mn
DISCHARGE
DITCHES
COLLECTION POND
MARSH POND
MARSH OR POND
PLAN 4
Net Alk
Mod Fe & Mn
Var Flow
DITCH
DEEP MARSH
SHALLOW MARSH
DEEP MARSH OR POND
DISCHARGE
AERATION
PLAN 5
Low Acidity
Low Fe & Mn
PLAN 6
High Acidity
High Fe & Mn
Variable Flow
ALD
DEEP POND
DEEP MARSH
ROCK FILTER
DEEP MARSH
AERATION
SHALLOW MARSH
DISCHARGE
ALKALINE RECHARGE
BACTERICIDE
DEEP COLLECTION POND
AERATION OR IN-LINE AERATOR
DEEP MARSH
SHALLOW MARSH
SO_4 REDUCTION CELL
SUBSURFACE FLOW ROCK FILTER
ALKALINE BED CELL
POLISHING POND
ALD or FRENCH DRAIN
CROSS-SECTION 7



PICAL STAGED, AEROBIC CONSTRUCTED WETLANDS

FIGURE 3

Simplified Flow Chart for Designing Staged, Aerobic Constructed Wetlands

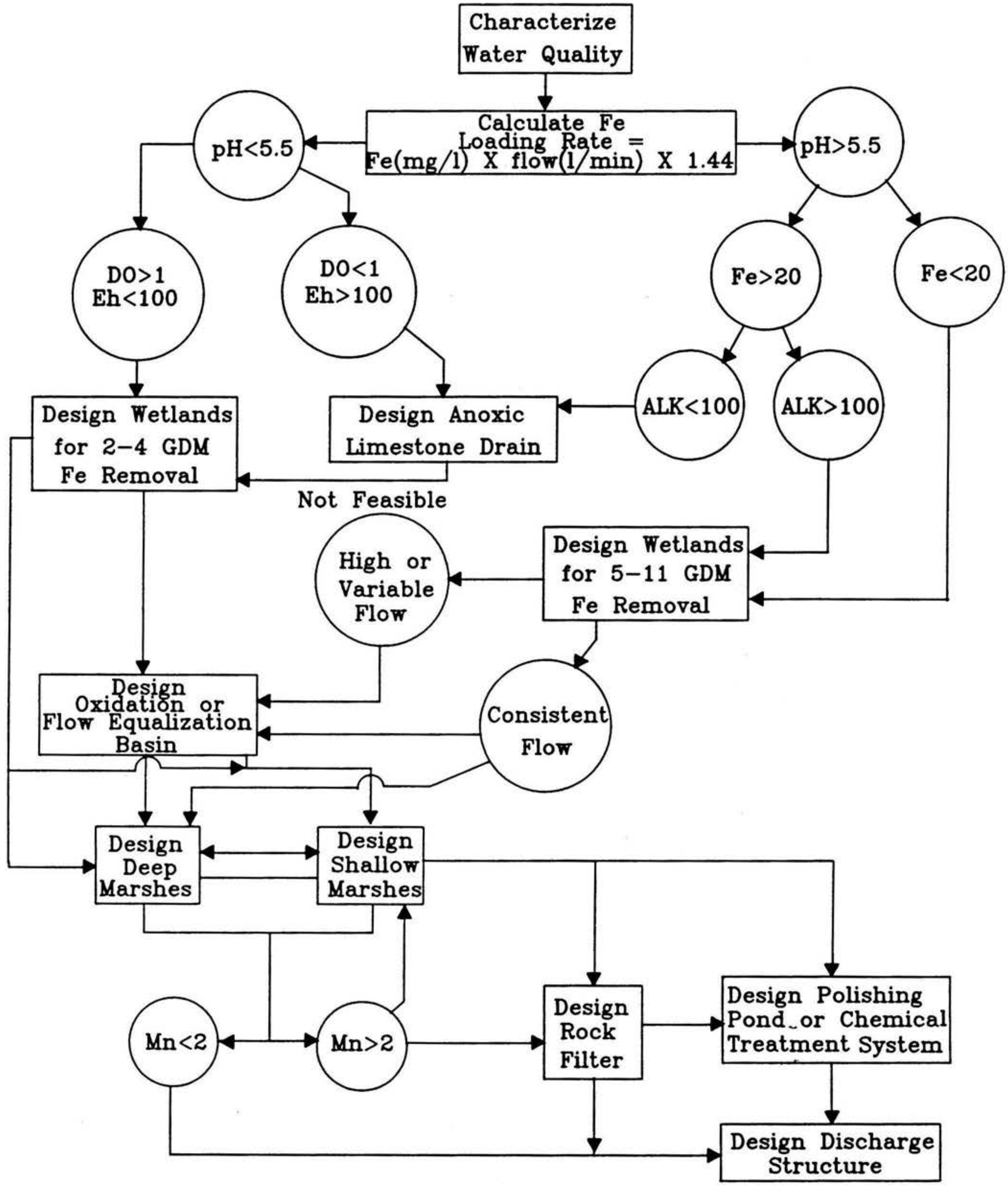


FIGURE 4

STAGED AEROBIC WETLANDS FOR ACID MINEWATER PURIFICATION (SaWAMP)

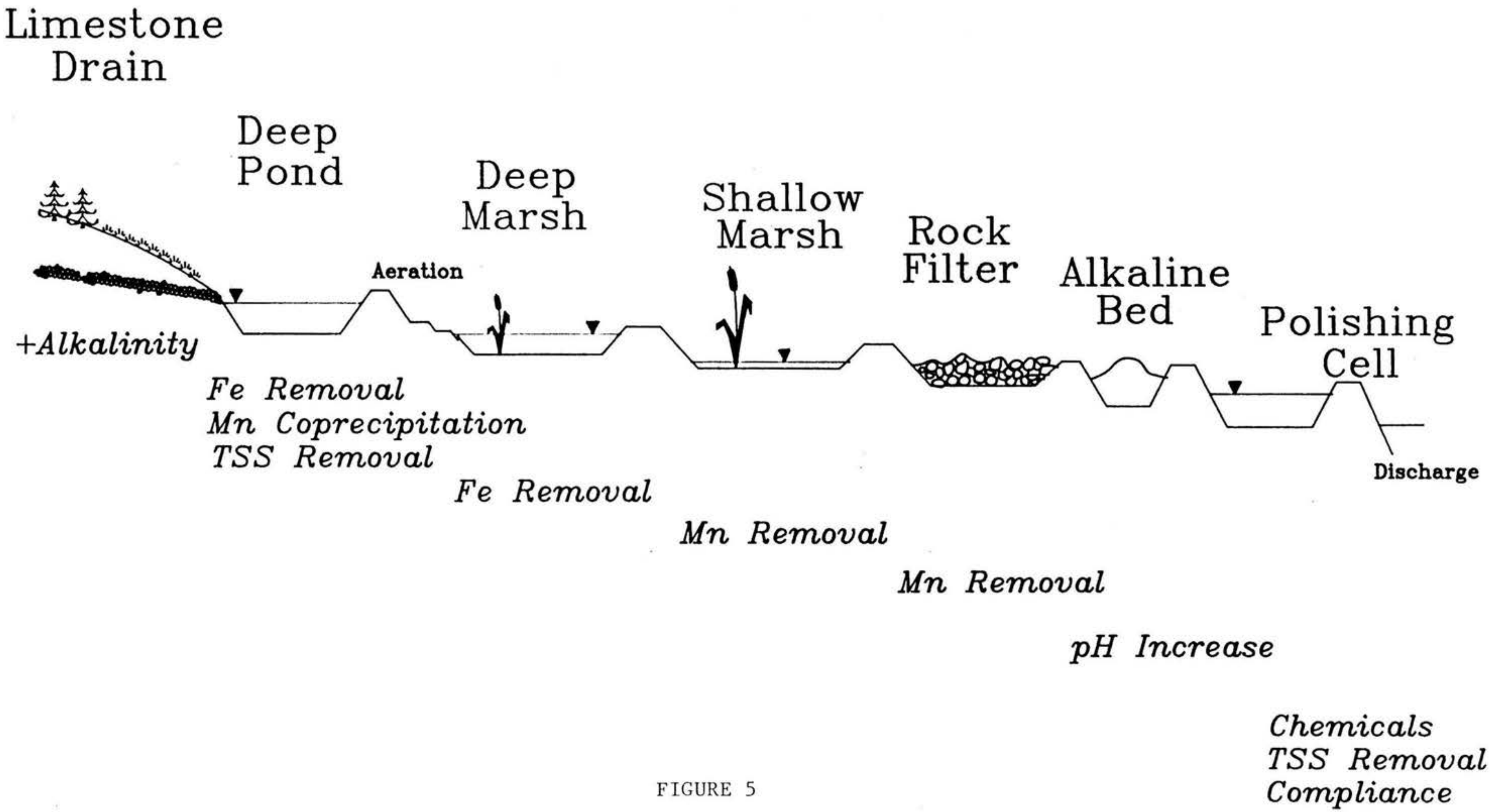


FIGURE 5

Geology

Soils and surface materials should be characterized for thickness, depth, classification and composition, use as a construction material, drainage characteristics, and erosion potential. Depth to bedrock should be determined to allow for various design considerations, although very shallow bedrock may preclude the use of constructed wetlands.

Topography affects cut and fill requirements, drainage and erosion characteristics, and slope stability. Number of cells in a wetlands may be dictated solely on the basis of topography. Detailed topographic surveys are usually not needed to design a wetlands but are convenient planning bases.

DESIGN

Major components of a wetlands treatment system which require design include general configuration/staging, collection structures, aeration structures, dikes, spillways, basins or wetlands cells, and pre- or post-treatment systems. There are numerous potential stages of a wetlands system and uncounted potential variations and configuration of the various stages, each based on site-specific conditions. Possible stages in a system include French drains, buried limestone drains, deep basins, shallow marshes, deep marsh-ponds, wet meadows, subsurface marshes, rock filters, bogs, polishing or treatment ponds, aeration structures, algae ponds, and others. Figure 2 shows plan schematics of several different examples of staged wetlands systems. Figure 3 shows a typical scheme for a staged wetlands system consisting of an anoxic drain, a deep marsh/pond cell, and a shallow marsh/pond cell followed by a polishing pond. Figure 4 suggests a simplified flow scheme for designing a staged constructed wetlands treatment system. By no means should this flow chart be considered a complete guideline, but rather a method at which to arrive at a conceptual design which must be refined based on the numerous site-specific characteristics. Because of the many types of pollutants in acid drainage which require different treatment methodologies, constructed wetlands can consist of several "stages" and components. Figure 5 depicts the SaWAMP model with the important stages in an aerobic style wetlands-based system. Each of these stages and their components are discussed below.

Collection Structures

If very different acid drainage compositions are under consideration, then combining them together may or may not be desirable. For example, if there is a low flow, very strong acid drainage and a high flow, low strength drainage, then it may be desirable to combine them, because wetlands processes may not be able to adequately treat the strong drainage itself. If the converse is true, then combining the two waters will only result in more water being treated by a non-wetlands treatment system.

French drains in the toe area of spoil can be used to discharge water into the first wetlands treatment unit. The design of the drain system should minimize mixing with uncontaminated water so as to avoid flow surges to the wetlands system.

Pipes are chronic O&M problems in acid drainage environments. If pipes are necessary to collect the seepage, the use of a gas trap at the exit and clean-out plugs should minimize these problems. It is important to exclude oxygen to avoid the precipitation of iron oxyhydroxides that can constrict the flow in the pipe, eventually rendering it useless.

Seeps can be collected in strategically located collection ponds or contour ditches that discharge into a collection pond or the first wetlands treatment unit. These structures can also serve as pre- or primary treatment units. This includes precipitate settling and possible chemical treatment, if required. The advantages of a collection pond include flow surge control and relatively constant head to the wetlands system. Dams and/or diversion ditches can also intercept surface acid mine drainage.

Inflow surge and constant head control are particularly important where the inflow is from surface drainage and/or heavily influenced by runoff. Surges from seeps and underground mines are usually dampened relative to those from surface drainage. The maintenance of a relatively constant head on the inflow to the wetlands system will provide the wetlands system with a relatively constant inflow rate and simplify design considerations. The wetlands system will operate in a relatively constant, steady-state condition, which minimizes hydraulic, vegetative, and substrate stresses. A collection pond or ditch with an elevated diversion ditch, spillway, or riser pipe is appropriate. Ideally, these should be located upstream from the wetlands system to protect it from storm surges. The retention capacity of a collection pond can be sized to contain typical "flood" or storm events. Some wetlands designs have a spillway at the end of the last treatment cell, but this will not protect the body of the wetlands from the effects of a storm surge eroding sediments and substrate. A sediment settling pond upstream of the wetlands cells will also remove material not requiring treatment in the wetlands treatment cells. The reduction of incoming sediment loads to the wetlands system will contribute to maximizing the useful life of wetlands treatment cells.

An additional type of collection structure is the anoxic limestone drain (ALD). Because this structure is an important pretreatment stage, it is discussed later and as Appendix 2.

Sizing Wetlands

The simplest rule to follow in constructing wetlands is the bigger, the better. Increased surface area and increased retention time improves overall performance. Increasing the size also increases the cost, so the minimal wetlands size for effective water treatment is desirable.

Wetlands size is a major design consideration which is being investigated by several researchers. The first size design guideline, 200 square feet per maximum flowing gallon per minute, was based on hydraulic loading and neglected any consideration of water chemistry (Kleinmann et al, 1983; Pesavento, 1984). More recently, chemical loading rates based on wetlands area and iron and manganese influent concentrations have been suggested as better parameters for sizing wetlands (Brodie et al, 1988; Brodie, 1990; Hedin, 1990; Stark et al, 1990; Hedin and Nairn, 1990; Stark et al, 1990).

Fe Loading and Removal
TVA Constructed Wetlands

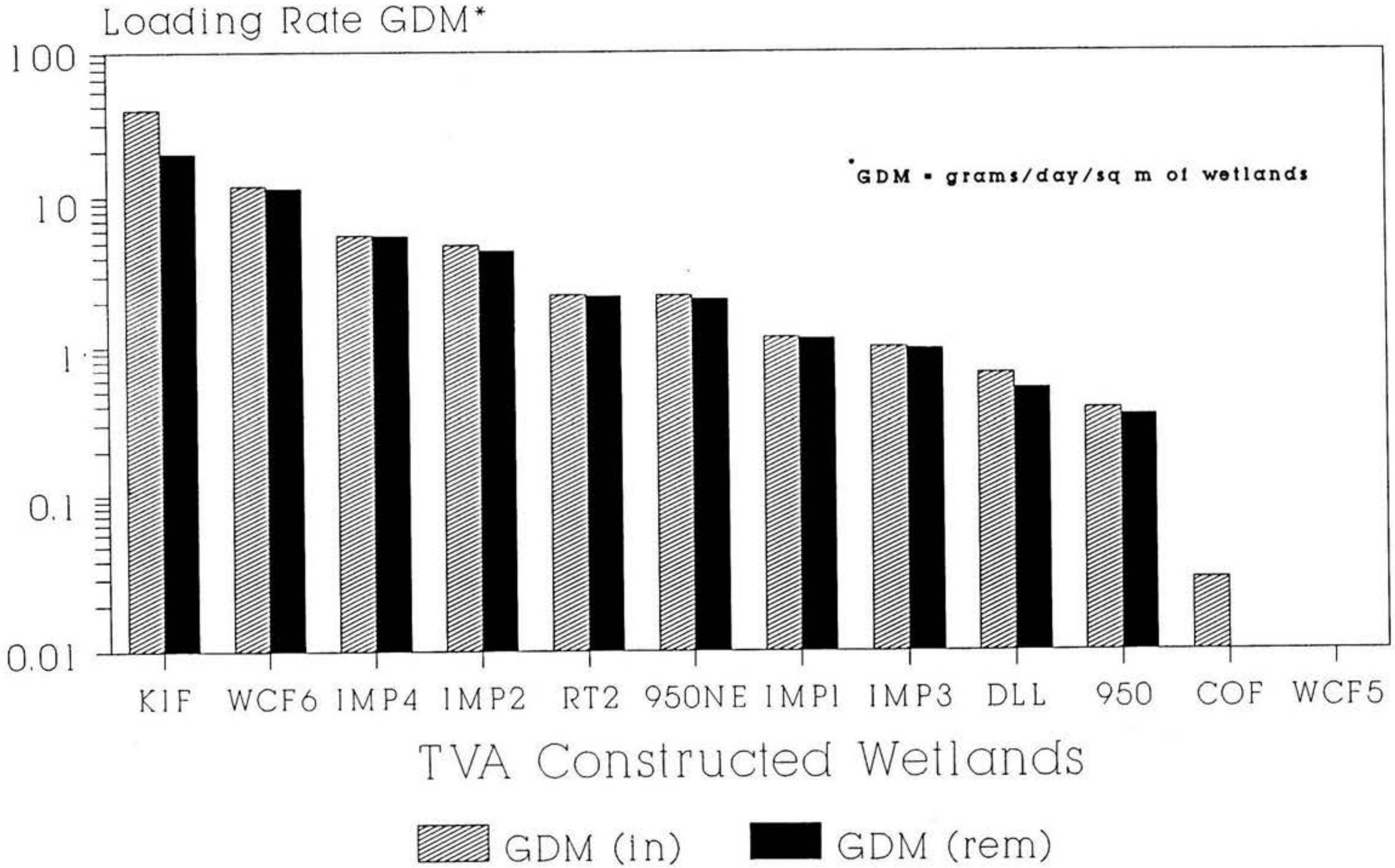


FIGURE 6

Wetlands sizing based on a single parameter (e.g., total Fe) is probably not appropriate because of the many active influences on pollutant active in a wetlands. These influences include influent pH, alkalinity and acidity, Fe concentration and form, Mn concentration, sulfate concentration, and average and maximum flow. Of these influences on wetlands sizing, the system must be designed to accommodate the maximum probable flow. Practically, this might correspond to the 100-year, 24-hour rainfall event being contained. However, with only preliminary chemical loading rate guidelines ranging from about 2.0 g/day/m^2 (GDM) to nearly 11 GDM of total Fe (see Figure 6), one can do a best practical estimate of wetlands size based on influent iron concentration and maximum probable flow. For example, a water with 50 mg/l Fe and a maximum flow rate of 150 l/min would be sized according to:

$$\text{Wetlands Area (A)} = \frac{[\text{Fe Conc. (mg/l)} \times \text{Flow (l/min)} \times 1.44]}{\text{Recommended Chemical Loading Rate (GDM)}}$$

$$A = [50 \text{ mg/l} \times 150 \text{ l/min} \times 1.44] \;/\; 2.0 \text{ GDM}$$

$$= 5400 \text{ sq. m}$$

If significant alkalinity is present in the influent, the larger loading rate may approach a sizing guideline.

$$A = [50 \text{ mg/l} \times 150 \text{ l/min} \times 1.44] \;/\; 11 \text{ GDM}$$

$$= 982 \text{ sq. m}$$

The Bureau of Mines has developed empirical sizing criteria, based on iron removal, that takes into account water chemistry as well as flow rates (Kleinmann et al, 1990). For influent water with a pH of 3.0-3.5 s.u., 1200 ft^2 of wetlands will remove, on average, a pound of iron a day. If the influent pH is 4-5 s.u. the wetlands is more efficient and less space is required: 500 ft^2 of wetlands will remove, on average, a pound of iron per day. If pH is > 6 s.u., and excess alkalinity is available, the efficiency doubles: 250 ft^2 will remove a pound of iron per day. For design purposes, a good rule of thumb is to double these area requirements to account for reduced effectiveness during winter and unexpected high loadings.

If the pH and/or manganese concentrations require treatment, additional space must be allotted to treat these parameters. The Tennessee Valley Authority estimates that, on average, to meet discharge criteria wetlands should be built 5 to 6 times larger than what the Bureau of Mines believes is required for iron removal alone.

Most wetlands have not been constructed as large as TVA would suggest is required, but most wetlands do not meet discharge criteria either. Approximately 80 % of the sites require chemical treatment to bring the effluent of the wetlands into compliance with regulatory limits (generally Fe $\leq$ 3 mg/l, Mn $\leq$ 2 mg/l, TSS $\leq$ 35 mg/l, and pH = 6-9 s.u.). However, even these wetlands are considered effective because they significantly decrease chemical treatment costs. Indeed, most wetlands constructed to treat acid mine drainage pay for themselves in less than a year by allowing the operator to use simpler, less expensive chemical treatment systems and/or to significantly reduce the amount of chemicals used.

Thus, sizing becomes a question of balancing available space and wetlands construction costs versus influent water quality and chemical treatment costs. Wetlands can be constructed as a biological pre-treatment step or as a potential alternative to chemical treatment; in either mode, wetlands can be effective, given the site conditions and the operating assumptions.

Depth

Depth of water in cells may vary according to the needs of the operator. Shallow (< 25 cm) marshes lend toward strong dissolved oxygen levels and oxidizing conditions but reduce lifespan of the cell, reduce retention capacity, enhance higher flow velocities, and may be subject to freezing in cold climates. Deeper cells (25-50 cm) decrease vegetation diversity, lend to lower dissolved oxygen levels and reducing conditions near the substrate, but increase the retention capacity and lifespan of the cell. Deeper cells may be most appropriate for moderate water quality or as the first stage in a wetlands system to accommodate rapid oxidation/precipitation of ferrous Fe.

Additionally, deeper cells, or deep spots within shallow cells, may enhance fish and wildlife habitat, provide recharge and wildlife refuge areas in the wetlands during dry periods, and improve hydraulic characteristics of the cell. Ideally, a cell should not be of a uniform depth, but should include shallow and deep marsh areas and a few deep (1 to 2 m) spots. Note that most readily available aquatic vegetation will not tolerate water depths greater than about 50 cm.

Wetlands Forms

Configuration of a staged wetlands system will vary depending on flow, water quality, and topography. Very large cells are subject to hydraulic short-circuiting and should be hydraulically chambered using simple, low or subsurface finger dikes, logs, riprap baffles or other structures. The most common flow path guides are hay bales. The theory is to maximize the contact volume or surface area and the effective detention time of the wetlands cell as well as avoid channelization or short-circuiting of the cell. An alternative is to have irregular or serpentine perimeters for the cells. Some wetlands have irregular islands in the cell. Preferably, a wetlands system should consist of several cells.

The geometry of the wetlands site , as well as flow control and water treatment considerations, may dictate the use of multiple wetlands cells. The intercell connections may also serve as aeration devices. If there are elevation differences between the cells, the interconnection should dissipate kinetic energy and not allow high energy water to enter a wetlands cell causing erosion and/or the mobilization of precipitates.

Multiple and sequential treatments, such as aerobic/anaerobic, may be required to treat low pH, high metal-content acid drainage. The order of dominant treatment cell mechanisms has been observed from a limited number of observations to be significant. Wetlands systems with anaerobic processes before aerobic processes have resulted in considerably diminished treatment effectiveness relative to using only aerobic processes. Data to date indicate that treatment cells dominated by aerobic processes should precede those dominated by anaerobic processes. Figure 3 depicts a consummate Staged Wetlands for Acid Minewater Purification (SWAMP).

Bottom slopes are not extremely critical to the operation of a wetlands. An exception may be a subsurface flow stage which uses deep beds of compost or other permeable organic material to induce sulfate reduction. Bottom slopes in these stages should be about 1-3 % upstream.

Cell length to width (L:W) ratios should be sufficient to prevent high velocities and channelization. Experience from municipal wastewater treatment wetlands suggests that L:W < 1.0 enhances treatment capabilities of a system.

<u>Substrates</u>

Substrates for a wetlands range from labor and cost-intensive crushed limestone/compost in sulfate reducing-type wetlands to lower cost in-situ materials such as mine spoil in aerobic wetlands. The Bureau of Mines has suggested a design for a treatment wetlands which uses about 30-50 cm of high calcium limestone covered by 20-30 cm of spent mushroom compost to induce sulfate reduction. The limestone enhances the alkalinity and buffering capacity of the wetlands flow, and the compost enhances sulfate reduction mechanisms in the system and provides a suitable growth medium for aquatic vegetation.

TVA has built numerous wetlands using only in-situ materials for substrates and primarily aerobic mechanisms for pollutant removals (Brodie, 1992a). These materials have included low organic sandy loams, silty loams, medium organic silty loams, and sandy to rocky mine spoils. Wetlands success at the TVA has not been correlated to the type of substrate used. The added expense of importing substrates is not recommended, but rather use of site, or in-situ materials to provide only a suitable growth medium.

To remove acidity, alkalinity must be generated by either limestone dissolution (as from an anoxic limestone drain) or bacterial sulfate reduction. The approach used in northern Appalachia is to route the aerobically-treated, low-iron effluent of a conventional constructed wetlands through composted organic substrate in a second series of wetlands, to use the acid-consuming activity of the sulfate-reducing bacteria. Although aerobic systems may be passively influenced by the presence of their substrate and associated biological activity, anaerobic processes dominate in the second system. The central themes in these treatment systems are substrates rich in organic matter to support sulfate reduction, vegetation to replace consumed organic matter, and a flow regime that is contained mainly in the substrate.

The common substrate is spent mushroom compost that is generally placed (not compacted) in a layer about 50 cm thick. Thicker layers cause densification at depth which reduces permeability to an ineffective level to promote transmissability of the acid drainage. Spent mushroom compost has a bulk density of about 0.65 g/cm^3 (1,100 pounds per cubic yard). A typical coverage for a .5 m (18 inches) thick substrate is about 3.2 m^2 per metric ton (3.5 square yards per ton). Other types of composted organic matter may be suitable as well.

Cattails or other emergent vegetation are planted in the substrate to stabilize it and provide organic matter to "fuel" the sulfate reduction process. As a practical tip, cattail plant/rhizomes should be planted well into the substrate prior to flooding the wetlands cell.

The flow regime in a sulfate reducing wetlands should be primarily within the substrate material. There are various ideas on inducing subsurface flow in the substrate, most of which have met with failure. Buried pipe systems have had limited operational life, but first demonstrated that significant water chemistry changes could be made on acid drainage using subsurface flow. While subsurface flow schemes are still in the experimental state, gravel packs to infuse and/or collect water in a wetlands cell have been used in some wetlands applications mostly for non-acid drainage wastewater. The greatest success, to date, has been at sites where the compost is sloped or piled a little higher than the free water surface of the wetlands cell, so that the water must flow through the compost. Water flows through the compost, eventually breaking out at the end, where it flows out of the first cell and into another cell.

In some cases (e.g., a groundwater recharge area), a liner may be required to protect groundwater resources and to simply retain water in the wetlands. Liners may be compacted clay soils (6-10 inches) or synthetic liners overlain by 8 or more inches of growth medium. Most aerobic wetlands are constructed using compacted clay and silt soils. The use of liners on a sand or soil base for the treatment cell may be rather expensive. There are occasional uses of plastic liners for ditches and intercell connections. Plastic liners have also been used on dam faces. The chemical resistance of plastic or rubber materials to aqueous hydrogen sulfide and the sulfate solutions of ferrous and ferric iron should be evaluated before use in a constructed wetlands. The use of bentonitic clays in some compositions of AMD may not result in the expected performance of the bentonite. There are different varieties of bentonites and these should be evaluated before use in an AMD environment.

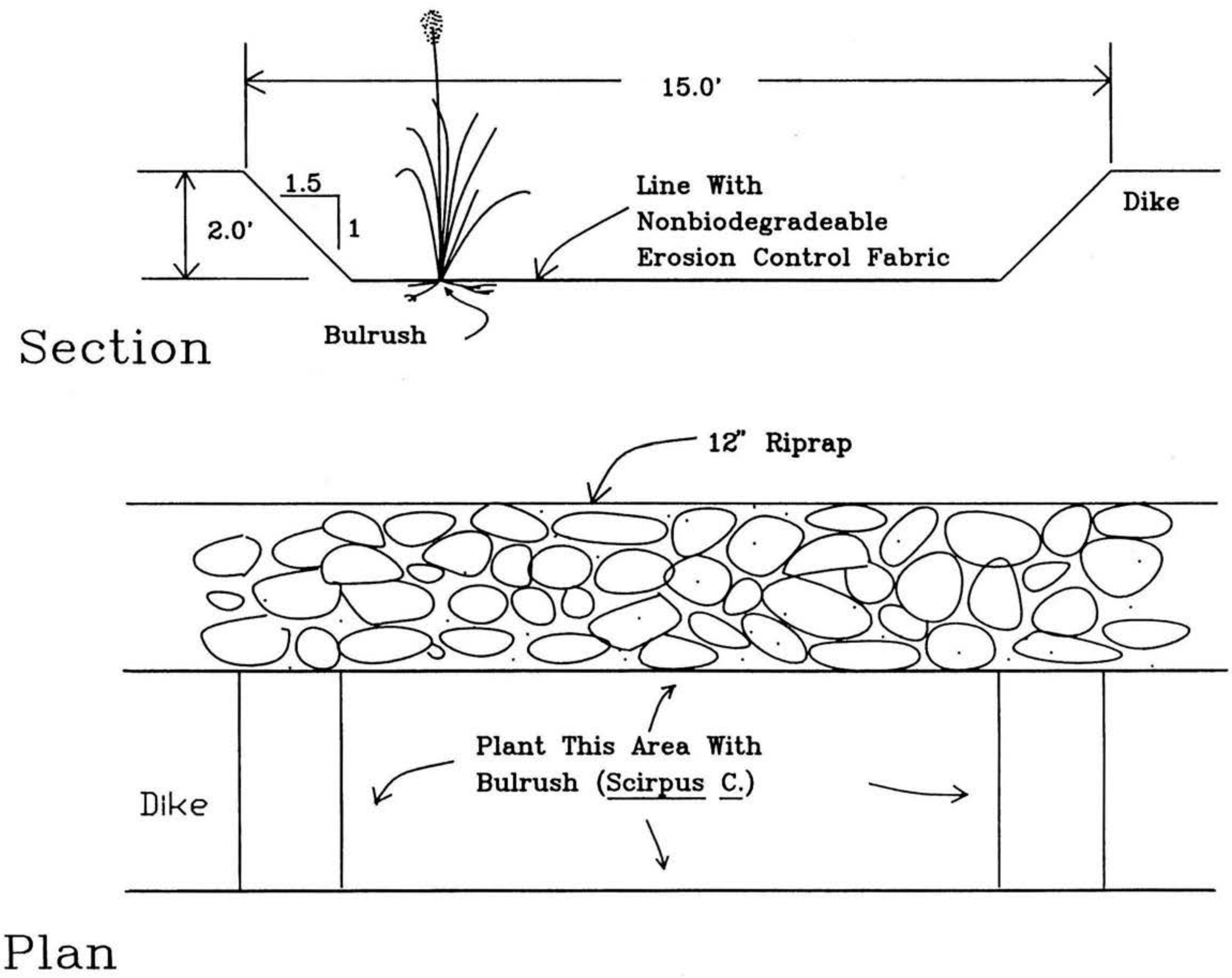
Dikes and Spillways

Dikes should be constructed of locally borrowed material (cell cuttings are ideal usually), adequately compacted and sloped minimally 2H:1V. Dikes tend to settle over several years and should therefore be constructed with about 2.5 ft. freeboard to ensure over the long term. Dike crest widths may vary. Wide dikes reduce wetlands area and increase the susceptibility to vehicular traffic. It is recommended to minimize dike widths and to place large tank bars at each end to discourage vehicles.

Spillways should be designed to pass the maximum probable flow. Figure 7 shows a typical design for a spillway. Spillways should consist of wide cuts in the dike with side slopes no steeper than 2H:1V, lined with non-biodegradable erosion control fabric, and coarse riprapped if high flows are expected. Proper spillway design can preclude high future maintenance costs due to erosion and/or failed dikes. Vegetated spillways overlying erosion control fabric provide natural and stable spillways. Other forms of spillways include pipes, risers, and various water level control structures. With best engineering design practices, most spillways will perform adequately. If pipes are used, small diameter (< 12") pipes should be avoided due to plugging from litter. Pipes should be PVC or coated for long-term stability. If desired, emergency spillways can be incorporated into the dike design.

Figure 7

TYPICAL CONSTRUCTED WETLANDS SPILLWAY



Pretreatment and Aeration

Aeration structures include simple splash areas, cascades, or more elaborate structures such as an in-line aeration system. Generally, the shallow depths in constructed wetlands, along with the spillway designs, provide for sufficient aeration to enhance metals removal and support aquatic life. If aeration structures are planned, their consumption of hydraulic potential should be considered. As aeration only provides enough oxygen to oxidize 50-70 mg/l ferrous iron to the more insoluble ferric form, acid drainage with higher concentrations of ferrous iron will require the operation of a series of aeration units-wetland cell combination. The wetlands cells are required to allow the oxygen in the aerated water to be consumed in oxidizing the ferrous iron and the resulting floc to settle out of suspension. At acid pH's,iron oxidation is primarily a function of bacterial activity but at circum-neutral pH's abiotic oxidation is also significant. A side effect of either oxidation process is a generation of acidity which in turn slows the oxidation process which is inversely proportional to pH. This acidity must be consumed and the pH raised in order to take better advantage of the next aeration/oxidation/precipitation stage. This acidity can be consumed by added alkaline materials or the alkalinity generated by bacterial sulfate reduction.

A new system which is being used in Tennessee to pretreat wetlands inflow is known as an anoxic limestone drain (ALD). These systems, which consist of limestone backfilled collection drains within the spoil, are covered with plastic and clay soil to maintain an anoxic state to prevent ferric iron armoring. Seepage through the trench picks up significant alkalinity which buffers the water against drastic pH decreases in the wetlands as ferrous iron oxidizes, hydrolyzes, and precipitates. Success with the systems is preliminary but impressive (Brodie et al, 1991).

Vegetation can be simply one species readily available from nurseries or nearby wetlands, or can be more exotic species adapted to a specific niche in the constructed wetlands. The least costly vegetation has been nursery stock planted in shallow water or saturated substrate. A more costly option is to transplant vegetation from nearby marshes. Preferably, a new system should be planted with several species, such as cattail (Typha sp.), bulrush (Scirpus), and rush (Eleocharis). Vegetation has traditionally been planted at about one-foot centers, but less dense planting may be acceptable, especially when using cattails. All dikes and disturbed areas should be revegetated immediately to minimize erosion and sedimentation into the wetlands.

A final note on design concerns the method of contracting a wetlands project. Set contracts, although good for planning purposes, are often less desirable because of the frequency of field changes in design of a system. Unless a wetlands has been thoroughly engineered and designed, it is usually cost-effective to complete a wetlands project through a contract operator on a cost-reimbursable basis, with adequate controls.

CONSTRUCTION

Heavy equipment used for constructing wetlands may vary, but usually consist of a small dozer and a larger dozer, a hydraulic excavator or backhoe, a loader, and a dump truck. Additionally, a hydroseeder may be useful.

After site mobilization of equipment, silt retention structures should be installed in and along the stream. The cells are then cleared and grubbed, rough graded, and the dikes are constructed. Emergency spillways are built, then the primary spillways. If flow or water level adjustment devices are not used, temporary pumping or delaying final spillway construction may be required to proceed with planting nursery stock. Full grown aquatic vegetation may be planted directly in deep ($< .5$ m) water as long as leaves are exposed to air. Planting cattails must be done carefully, setting the whole root ball into the substrate. Breaking the cattail stem at the water level prevents wind throw and stimulates root growth. Bulrush may simply be placed on the substrate. Wetlands have generally been fertilized once to get them going. A typical list of materials would include crushed limestone, spent mushroom compost, riprap, piping, erosion control fabric, wood, sacrete or concrete, seed, mulch, fertilizer, fencing, and aquatic vegetation. Labor requirements include a site engineer, two equipment operators, labor crew, and foreman.

OPERATION AND MAINTENANCE

During the initial start-up period (4 to 8 months), water levels should be closely monitored if nursery stock was used. Otherwise, the start-up period is shortened to weeks. Operational problems can be attributed to inadequate design, unrealistic expectations, pests, inadequate construction methods, or nature-induced problems. If properly designed and constructed, a wetlands treatment system can be operated with a minimum amount of attention and money.

Probably the most common maintenance problem is dike and spillway stability. Reworking slopes, rebuilding spillways, and increasing freeboard can all be avoided by proper design and construction using existing guidelines for such construction.

Pests often plague wetlands with operational problems. Muskrats will burrow into dikes, posing leakage and potentially catastrophic failure problems, and will uproot significant amount of cattails and other aquatic vegetation. Muskrats can be discouraged by linking dike inslopes with chain-link fence and/or riprap to prevent burrowing. Beavers cause water level disruptions due to damming and also seriously damage vegetation. They are very difficult to control once established. Small diameter pipes traversing wide spillways ("three-log structures") and trapping have had limited success in beaver control. Large pipes with 90-degree elbows on the upstream end have been used as spillways in beaver-prone areas. Otherwise, shallow ponds with dikes with shallow slopes toward wide, riprapped spillways may be the best design for a beaver infested system (i.e., learn to live with them).

If mosquitoes are a problem, mosquitofish (Gambusia affinis) may be introduced into the wetlands. Other insects, such as the armyworm, have devastated monocultural wetlands by their appetite for cattails (Snoddy et al, 1989). Planting numerous species in a system will minimize such problems, although it may be necessary to apply an insecticide such as Lorsban until natural predators control certain insect pests. Even bats may provide a means of insect control at remote sites (Tuttle, 1988).

COSTS

Figure 8 shows the major items contributing to the cost of a constructed wetlands. These include costs for land acquisition, engineering and design, construction (equipment, labor, and materials), and operation and maintenance. Costs will vary based on numerous factors which include geotechnical considerations (bedrock depth, availability of construction materials, liners, etc.), land acquisition costs, and labor and equipment rates. However, costs per square foot of wetlands generally range from about $ 0.50 to $ 3.00, and average just over $ 1.00.

FINAL NOTES

The author, on behalf of the Tennessee Valley Authority, is pleased to share his experiences and background on constructed wetlands. Design and design concepts for constructed wetlands are relatively new technologies. Concepts, procedures, and methods introduced in this report may or may not be useful for a particular situation. Prospects for application of constructed wetlands should be examined by scientists and engineers with appropriate training and experience. When the application is viable, systems design and carefully staged, monitored, and documented development only by experienced persons are recommended. Further, because of the potential importance of wetlands-based technology to mitigate many serious water quality problems, it is essential that those who build and operate such systems document and report on their successes and failures in order that the scientific, engineering, and regulatory communities can advance the state-of-the-art of constructed wetlands based on knowledge and data.

TYPICAL COST BREAKDOWN
TVA Constructed Wetlands

DESIGN	$6000
PERMITTING	1000
LAND ACQUISITION	6000
CONSTRUCTION	
- Equipment & labor	12,000
- Materials	6000
- Supervision	4000
OPERATION & MAINTENANCE	9000
MISCELLANEOUS	6000
TOTAL	$ 50,000

FIGURE 8

LITERATURE REVIEW AND CITATIONS

Ackman, T.E. and R.L.P. Kleinmann. 1984. In-Line Aeration and Treatment of Acid Mine Drainage. U.S. Bureau of Mines Rept. of Investigations RI8868. 9 pp.

American Public Health Association. 1989. Standard Methods for the Examination of Water and Wastewater. Washington, D.C. 874 p.

Ansted, J.P. 1982. Removal of Heavy Metal Ions from Aqueous Solution by Ion Exchange on Sulfuric Acid Treated Peat. Master's Thesis, Colorado School of Mines. Golden, Colorado.

Aulio, Kai. 1982. Nutrient Accumulation in Sphagnum Mosses. II. Intra and Interspecific Variation in Four Species from Ombrotrophic and Minerotrophic Habitats. Am. Bot. Fennici. Vol. 19. pp. 93-101.

Baas Becking, L.C. M., T. R. Kaplan and D. Moore. 1960. Limits of the Natural Environment in Terms of pH and Oxidation-Reduction Potentials. Journal of Geology 68 (3):243.

Bedish, J.W. 1976. Cattail Moisture Requirements and their Significance to Marsh Management. Am. Medl. Nat. 78:288-300.

Belkevich, P.I., K.A. Gaiduk, and L.R. Chistova. 1976; Role of Peat in Decontamination of the Environment. Chem. Abst. 89(24):200167J.

Bennett, E.D. 1969. Algae in Relation to Mine Water. Castanea Vol. 34, pp. 306-328.

Bennett, P.G. and T.H. Jeffers. 1990. Removal of Metal Contaminants from a Waste Stream Using Biofix Beads Contaianing Sphagnum Moss. In: Proc. Western Regional Symp. on Mining and Mineral Processing Wastes. Berkeley, CA.

Boelter, D.H. and E.S. Verry. Peatland and Water. 1977. USDA Forest Service General Technical Report NC31.

Brezonik, P.J. et al. 1981. Water Quality Studies. In: W.R. Fritz and S.C. Helle (eds.). Tertiary Treatment of Wastewater Using Flow-through Wetlands Systems. Boyle Engineering. Orlando, FL.

Britt, C.R. and G.A. Brodie. 1990. Wetlands and Related Issues of the Flat Woods Coal Lease and Caryville Industrial Park II: A Case Study of TVA's Coal Leasing Process. In: Graves, D.H. (ed.). Proc. 1990 Nat. Symp. of Mining. University of Kentucky BU 153. Lexington, KY. p. 155-162.

Brodie, G.A. 1989. Selection and Evaluation of Sites for Constructed Wastewater Treatment Wetlands. In: Hammer, D.A. (ed.). Wetlands for Wastewater Treatment. Lewis Publishers, Inc. Chelsea, MI. pp. 307-318.

Brodie, G.A. 1990a. Treatment of Acid Drainage Using Constructed Wetlands - Experiences of the Tennessee Valley Authority. In: Graves, D.H. (ed.), Proceedings, 1990 National Symposium of Mining, University of Kentucky BU 153, Lexington, KY, pp. 77-83.

Brodie, G.A. 1990b. Constructed Wetlands for Treating Acid Drainage-Practical Considerations of Design, Construction, and Operation. Manual for Workshop Presented at 12th Annual National Association of Abandoned Mine Land Programs Conference. Breckinridge, CO.

Brodie, G. A. 1990c. Constructed Wetlands for Treating Acid Drainage at TVA Coal Facilities. In: Proc. Annual Nat'l Assoc. of Abandoned. Mined Lands Program Conference. Breckenridge, CO.

Brodie, G.A. 1990d. Constructed Wetlands for Treating Acid Drainage at Tennessee Valley Authority Coal Facilities. In: P.F. Cooper an B.C. Findlater (eds.). Constructed Wetlands in Water Pollution Control. Pergamon Press. Elmsford, NY. p.461-470.

Brodie, G.A., 1990e. Unpublished Results of Current Research Using Alkaline Beds for Increasing Constructed Wetlands Effluent pH. Project co-funded by the Pennsylvania Electric Company and the Tennessee Valley Authority.

Brodie, G. A. 1991a. Achieving Compliance with Staged, Aerobic, Constructed Wetlands. In: Proceedings, 1991 Annual Mtg. of the ASSMR. Durango, CO. p. 151-174.

Brodie, G. A. 1991b. Design, Construction and Operation of Staged Aerobic Wetlands Systems to Treat Acid Drainage. Manual of Workshop Presented at 1991 Annual Meeting of the ASSMR. Durango, CO.

Brodie, G.A. 1991c. Staged, Aerobic Constructed Wetlands for Acid Drainage and Stormwater Control. Manual of Short Course Presented at the 34th Annual Meeting of the Association of Engineering Geologists. Chicago, IL.

Brodie, G.A. 1991d. Engineered Wetlands for Effective Treatment of Acid Drainage-Applications, Results, and Prospects in the Tennessee Valley. In: Proc. 34th Annual Meeting of the Association of Engineering Geologists. Greensburg, PA. p.558-568.

Brodie, G.A. 1992a. Staged, Aerobic Constructed Wetlands to Treat Acid Drainage - Case History of Fabius Impoundment 1 and Overview of the Tennessee Valley Authority's Program. In: Moshiri, G.A. (ed.). Constructed Wetlands for Water Quality Improvement. Proceedings of an International Conference. Lewis Publishers, Inc. Chelsea, MI. In press.

Brodie, G.A., 1992b. Unpublished Results of Current Research Using Alkaline Beds for Increasing Constructed Wetlands Effluent pH. Project co-funded by the Pennsylvania Electric Company and the Tennessee Valley Authority. In Preparation.

Brodie, G.A., C.R. Britt, 1992. Aerobic, Wetlands - Based Acid Drainage Treatment Using Anoxic Limestone Drains, Program Overview and Case History of TVA's Kingston Constructed Wetlands. In: Proceedings Thirteenth Annual West Virginia Surface Mine Drainage Task Force Symposium, Morgantown, W.V.

Brodie, G.A., C.R. Britt, H.N. Taylor. 1991. Use of Passive Anoxic Drains to Enhance Performance of Acid Drainage Constructed Wetlands. In: Proceedings 1991 National Meeting of the ASSMR. Durango, CO. p.211-228.

Brodie, G.A., C.R. Britt, H.N. Taylor, D. Turner and T.M. Tomaszewski. 1990. Passive Anoxic Alkaline Drains to Increase Effectiveness of Wetlands Acid Drainage Treatment Systems. In: Proceedings of 12th Annual National Association of Abandoned Mine Land Programs Conference. Breckinridge, CO.

Brodie, G.A., C. R. Britt, T. M. Tomaszewski, H. N. Taylor, 1992. Anoxic Limestone Drains to Enhance Performance of Aerobic Acid Drainage Treatment Wetlands - Experiences of the Tennessee Valley Authority. In: Moshiri, G. (ed.)., Constructed Wetlands for Water Quality Improvement - Proc. of an Int'l Conf. Lewis Publishers. Chelsea, MI. In Press.

Brodie, G.A., D.A. Hammer, and D.A. Tomljanovich. August 1986. Man-made Wetlands for Acid Mine Drainage Control. Presentation for the Eighth Annual National Abandoned Mine Land Conference. Billings, MT.

Brodie, G.A., Hammer, D.A., and Tomljanovich, D.A. 1987. Treatment of Acid Drainage from Coal Facilities with Man-Made Wetlands. In: K.R. Reddy and W.H. Smith (eds.). Aquatic Plants for Water Treatment and Resource Recovery. Magnolia Publ. Inc. Orlando, FL. pp. 903-912.

Brodie, G.A., Hammer, D.A., and Tomljanovich, D.A. 1988. Constructed Wetlands for Acid Drainage Control in the Tennessee Valley. In: Mine Drainage and Surface Mine Reclamation. U.S. Bureau of Mines Information Circular 9183, Vol. 1, pp. 325-351.

Brodie, G.A., Hammer, D.A., and Tomljanovich, D.A. 1988. Constructed Wetlands for Treatment of Ash Pond Seepage. In: Hammer, D.A., (ed.), Constructed Wetlands for Wastewater Treatment, Lewis Publishers, Inc., Chelsea, MI, pp. 307-318.

Brodie, G.A., Hammer, D.A., and Tomljanovich, D.A. 1989. Treatment of Acid Drainage with a Constructed Wetlands at the Tennessee Valley Authority 950 Coal Mine. In: Hammer, D.A. (ed.), Constructed Wetlands for Wastewater Treatment, Lewis Publishers, Inc., Chelsea, MI, pp. 211-220.

Brooks, R.P. 1984. Optimal Designs for Restored Wetlands. In: J.E. Burris, Treatment of Mine Drainage by Wetlands. Contribution No. 264 of the Dept. of Biology, The Pennsylvania State University.

Brooks, R.P., D.E. Samuel, and J.B. Hill (editors). Wetlands and Water Management of Mined Lands. Proceedings of a Conference held 23-24 October 1985. The Pennsylvania State University, University Park. 400 pp.

Bureau of Mines. 1988. Mine Drainage and Surface Mine Reclamation, Vol. 1: Mine Water and Mine Waste, Bu Mines IC 9183. Contains a number of relevant references.

Byron, C.J., 1985. "Man-Made Wetlands as a Post-Mining Land Use: Regulatory Issues and Conflicts," Proceedings, Wetlands and Water Management on Mined Lands, ed. by, R. P. Brooks, D.E. Samuel, and J.B. Hill, Pennsylvania State University, State College, PA, October 23-24, pp. 353-364.

Calabrese, J. P., A. J. Sextone, D. K. Bhumbla, J. C Sencindiver, G. K. Bissonnette, and J. G. Skousen. 1991. Chemical and Microbiological Modification of Acid Mine Drainage Using Constructed Typha Wetlands. In: Proc. 12th Ann. WV Surface Mine Drainage Task Force Symposium. Morgantown, WV.

Cardamone, M.A., J.R. Taylor and W.J. Mitsch, 1984. Wetlands and Coal Surface Mining: A Management Handbook, Available Free From the Authors at University of Louisville, Louisville, KY, 99 pp.

Chan, E., Bursztynsky, T.A., Hantsche, W., and Litwin, Y.J., 1982, "The Use of Wetlands for Water Pollution Control," EPA600/2-82-086, 261 pp.

Chan, E., et al. 1982. The Use of Wetlands for Water Pollution Control. Municipal Environmental Research Laboratory, EPA No. PE83-107-466.

Clymo, R.S. 1973. The Growth of Sphagnum: Some Effects of Environment. Journal of Ecology, Vol. 61, p.849-869.

Clymo, R.S. 1964. The Origin of Acidity in Sphagnum Bogs. Bryologist, 67:427-431.

Clymo, R.S. 1963. Ion exchange in Sphagnum and its Relation to Bog Ecology. Annals of Botany, N.S. 27 (106): 309-323.

School of Forestry and Environmental Studies. Duke University. Masters Degree Project. Durham, NC.

Council on Environmental Quality, 1978. National Environmental Policy Act - Regulation, 40 Code of Federal Regulations 1500-1508, 43 Federal Register 55990, as amended.

Cowardin, L., V. Carter, F. Golet, and E. LaRoe. 1976. Interim Classification of Wetlands and Aquatic Habitats of the United States USDI - Fish and Wildlife Service.

Cravotta, C.A., K.B.C. Brady, M.W. Smith, and R.L. Beam. 1990. Effectiveness of the Addition of Alkaline Materials at Surface Coal Mines in Preventing or Abating Acid Mine Drainage: part 1: Geochemical Considerations. Pages 221-225 In J. Skousen et al., eds. Proceedings of the 1990 Mining and Reclamation Conference and Exhibition, Volume 1. W.V. Univ. Publication Services. Morgantown, WV.

Dvorak, D.H., R.S. Hedin, H.M. Edenborn, and P.M. McIntire. 1991. Treatment of Metal-Contaminated Water Using Bacterial Sulfate Reduction: Results from Pilot-Scale Reactors. In: Proceedings, 1991 Annual Mtg. of the ASSMR. Durango, CO. p.109-121.

Dvorak, D.H., R.S. Hedin, H.M. Edenborn, and P.M. McIntire. 1991. Treatment of Metal-Contaminated Water Using Bacterial Sulfate Reduction: Results from Pilot-Scale Reactors. Proceedings of the 1991 AIME Annual Meeting. Denver, CO.

Eger, P., and K. Lapakko. 1988. Nickel and Copper Removal From Mine Drainage by a Natural Wetland. Mine Drainage and Surface Mine Drainage and Surface Mine Reclamation. Mine Drainage and Surface Mine Reclamation, Vol. I, mine Water and Mine Waste, Bureau of Mines Information Circular 9183. Pittsburgh, PA. p.301.

Eger,P., and I. Lapakko. 1989. Use of Wetlands to Remove Nickel and Copper From Mine Drainage in Constructed Wetlands for Wastewater Treatment. In: Hammer, D.A. (ed.), Constructed Wetlands for Wastewater Treatment, Lewis Publ. Chelsea, MI. p.780.

Eger, P., G. Melchert, D. Antonson, and J. Wagner. 1991. The Use of Wetland Treatment to Remove Trace Metals from Mine Drainage at LTV's Dunka Mine. Minnesota Department of Natural Resources, Division of Minerals, Minneapolis.

Eger, P., G. Melchert, D. Antonson, and J. Wagner. 1992. The Use of Wetland Treatment to Remove Trace Metals from Mine Drainage. In: G. Moshiri (ed.). Constructed Wetlands for Water Quality Improvement- Proc. of an Int'l Conf. Lewis Publishers, Inc. Chelsea, MI. In press.

Emerick, J.C. and E.A. Howard. 1988. Using Wetlands for the Control of Western Acid Mine Drainage. Soc. Mining Engr. Rept. 88-173 SME Ann. Meeting.

Faulkner, S.P., and C. J. Richardson. 1990. Biogeochemistry of Iron and Manganese in Selected TVA Constructed Wetlands Receiving Acid Mine Drainage. Duke Wetland Center Publication 90-03. Durham, NC.

Faulkner, S.P., and C. J. Richardson. 1990. Iron and Manganese Fractionation in Constructed Wetlands Receiving Acidic Mine Drainage.
Forstner, U. and G.T.W. Wittman. 1981. Metal Pollution in the Aquatic Environment. Springer-Verlag. New York. 486 p.

Fennessy, S. and W.J Mitsch. 1990. Design and Use of Wetlands for Renovation of Drainage from Coal Mines. In: S.E. Jorgenson and W.J. Mitsch (eds.). Ecological Engineering: an Introduction to Ecotechnology. J. Wiley and Sons. New York.

Frayer, W.E., T.J. Monohan, D.C. Bowden, and F.A. Graybill. 1983. Status and Trends of Wetlands and Deepwater Habitats in the Conterminous United States, 1950's to 1970's Dept. of Forest and Wood Science. Colorado State University. Ft. Collins, CO. 32 p.

Gandy, L.C., S.J. Formica, and M.A. Gross. 1991. An Evaluation of Vertical Flow Sulfate Reducing Wetlands to Treat Low pH, Low Sulfate Acid Mine Drainage Using Column Experiments. In: D.H. Graves (ed.). Proc. National Symposium on Mining, Univ. of Kentucky. Lexington. p.81-93.

Frostman, T.M. 1992. A Peat/Wetland Treatment Approach to Acidic Mine Drainage Abatement. In: G. Moshiri, (ed.). Constructed Wetlands for Water Quality Improvement, Proc. of an Int'l Conf. Lewis Publishers. Chelsea, MI. In Press.

Gerber, D.W., J.E. Burris, and R.W. Stone. 1985. Removal of Dissolved Iron and Manganese Ions by a Sphagnum Moss System. In: R.P. Brooks et al. (eds.), Wetlands and Water Management on Mined Lands, Proc. of a Conf., October 1985, the Pennsylvania State University.

Girts, M.A., Kleinmann, R.L.P., and Erickson, P.M.. 1987. Performance Data on Typha and Sphagnum Wetlands Constructed to Treat Coal Mine Drainage. In: Proceedings of 8th Annual Surface Mine Drainage Task Force Symposium. Morgantown, WV.

Gordon, J.A. and Burr, J.L., 1989. "Treatment of Manganese From Mining Seep Using Packed Columns." Journal of Environmental Engineering, Vol. 115, No. 2.

Gregory E., and J.T. Staley. 1982. Widespread Distribution of Ability to Oxidize Manganese Among Freshwater Bacteria. Applied and Environmental Microbiology, 44:2.

Gross, M.A., S.J. Formica, L.C. Gandy, and J. Hestir. 1992. A Comparison of Local Waste Materials for Sulfate Reducing Wetlands Substrate. In: G. Moshiri (ed.). Constructed Wetlands for Water Quality Improvement. Proc of an Int'l Conf. Lewis Publishers, Inc. Chelsea, MI. In Press.

Guertin, Deforest, J.C. Emerick, and E.A. Howard. 1985. Passive Mine Drainage Treatment Systems: A Theoretical Assessment and Experimental Evaluation.

Hammack, R.W. and R.S. Hedin. 1989. Microbial Sulfate Reduction for the Treatment of Acid Mine Drainage: A Laboratory Study. In: Proc. Conf. Reclamation, a Global Perspective. Alberta Land Conserv. and Reclam. Council Rept. No. RRTAC 89-2. p. 673-680.

Hammer, D.A. (ed.). 1989. Constructed Wetlands for Wastewater Treatment. Lewis Publishers, Inc., Chelsea, MI, 831 pp.

Hammer, David E. and Robert H. Kadlec. 1983. Design Principles for Wetland Treatment Systems. EPA No. PB-83-188-722.

Harris, R.L., et al. 1984. Treatment of Mine Drainage from Abandoned Mines by Biological Iron Oxidation and Limestone Neutralization. Peer Consultants Report prepared for Bureau of Mines under Contract J0113033, 113 pp., available from Robert Kleinmann, Bureau of Mines, Pittsburgh, PA.

Hedin, R.S. 1989. Wetlands Geology and Conservation: Emphasis in Pennsylvania. S.K. Majumdar, R.P. Brooks, F.K. Brenner and R.W. Tiner, Jr. (eds.). The Pennsylvania Academy of Science. pp. 349-362.

Hedin, R.S., 1989. Treatment of Coal Mine Drainage with Constructed Wetlands. In: Majumbar, S.K., et al. (eds.), Wetlands Ecology and Conservation: Emphasis in Pennsylvania, The Pennsylvania Academy of Science, Easton, PA, pp. 349-362.

Hedin, R.S., D.H. Dvorak, et al. 1991. Use of a Constructed Wetland for the Treatment of Acid Mine Drainage at the Friendship Hill Nat'l Historic Site, Fayette County, PA. Technical Report to the National Park Service. U.S. Bureau of Mines. Pitsburgh, PA.

Hedin, R.S. and R.W. Nairn. 1990. Sizing and Performance of Constructed Wetlands: Case Studies. In: Proc. 1990 Mining and Reclamation Conf., WV University, Morgantown, WV, p. 393-401.

Hedin, R.S. , R. Hammack, and D. Hyman. 1989. Potential Importance of Sulfate Reduction Process in Wetlands Constructed to Treat Mine Drainage. In: Constructed Wetlands For Wastewater Treatment. D.A. Hammer (ed.). Lewis Publishers, Chelsea, MI. p.508-514.

Hedin, R.S., R.W. Narin, and H.M. Edenborn. 1992. Contaminant Removal Capabilities of Wetlands Constructed To Treat Coal Mine Drainage. In: G. Moshuri (ed.). In: G. Moshiri (ed.). Constructed Wetlands for Water Quality Improvement. Proc of an Int'l Conf. Lewis Publishers, Inc. Chelsea, MI. In Press.

Hellier, Jr., W.W. 1989. Constructed Wetlands in Pennsylvania: An Overview. In: J. Salley et al., (eds). Biohydrometallurgy, Proc. of the Int'l Symp. Jackson Hole, WY. pp. 599-611.

Hem, J.D. 1960. Some Chemical Relationships Among Sulfur Species and Dissolved Ferrous Iron. U.S. Geological Survey Water-Supply Paper 1459-C.

Hem, J.D. 1961. Stability Field Diagrams as Aids in Iron Chemistry Studies. Jour. AWWA 53 (2):211.

Hem, J.D. 1963a. Chemical Equilibria and Rates of Manganese Oxidation. U.S. Geological Survey-Water Supply Paper 1667-A.

Hem, J.D. 1963b. Manganese Complexes with Bicarbonate and Sulfate in Natural Water. Jour. Chem. and Eng. Data 8(1):99-101.

Hem, J.D., 1981. Rates of Manganese Oxidation in Aqueous Systems. Geochemica et Cosmechimica Acta, 45:1369.

Herlihy, A.T. and A.L. Mills. 1985. Sulfate Reduction in Freshwater Sediments Receiving Acid Mine Drainage. Applied and Environmental Microbiology. 49:179-186.

Herricks, Edwin E. 1982. Biological Treatment of Acid Mine Drainage. University of Illinois Water Resources Center, Research Report No. 173.

Hiel, M.T. and F.J. Kerins Jr. 1988. The Tracy Wetlands: A Case Study of Two Passive Mine Drainage Treatment Systems in Montana. In: Proc. Mine Drainage and Surf. Mine Reclamation Vol. 1. U.S. Bureau of Mines Information Circular IC 9183.

Holcombe, L.A. 1977. Adsorption and Desorptionin Mine Drainages. Thesis No. 1944. Colorado School of Mines. Golden, CO. 101 pp.

Holm, J.D. 1983. Passive Mine Drainage Treatment: Selected case studies. In: Medin, A. and M. Anderson (eds.), Process of the ASCE Specialty Conference, 1983, National Conference on Environmental Engineering Boulder, CO.

Holm, J.D. 1985. Passive Mine Drainage Treatment. Colorado Mined Lane Reclamation Division, Denver, CO.

Holm, J.D. and P. Overynder. 1987. Policy and Performance Considerations for Passive Mine Drainage Treatment Systems in Colorado. In: Proc. Nat'l Western Mining Conf.

Huntsman, B.E. 1986. Sphagnum-Dominated, Man-Made Wetlands Used for Acid Mine Drainage Abatement: Preliminary Performance Evaluation. Proceeding from 7th Annual West Virginia Surface Mine Drainage Task Force Symposium Morgantown, West Virginia.

Huntsman, B.E., R.L.P. Kleinmann, T.O. Tierman. 1985. Hydrologic and Geochemical Considerations in Maintaining Man-Made Wetlands Constructed for Acid Mine Drainage Abatement. In: R.P. Brooks, et al. (eds.), Wetlands and Water Management on Mined Lands, Process of a Conference, October 1985, The Pennsylvania State University.

Huntsman, B.E., J.G. Solch, and M.D. Porter. 1978. Utilization of Sphagnum Species Dominated Bog for Coal Acid Mine Drainage Abatement. GSA (91st Annual Meeting) Abstracts, Toronto, Ontario.

Hyde, H.C., R.S.Ross, and F. Dengen. 1982. Technology Assessment of Wetlands for Municipal Wastewater Treatment. Municipal Env. Res. Lab., EPA, Cincinnati, OH.

Jenne, E.A. 1968. Controls on Mn, Fe, Co, Ni, Cu, and Zn Concentrations in Soils and Water; the Significant Role of Hydrous Mn and Fe Oxides. Am. Chem. Soc., Adv. Chem. Ser., 73:337-387.

Jennet, J.C., J.E. Smith, and J.M. Hassett. 1983. Factors Influencing Metal Accumulation by Algae. U.S. Environmental Protection Agency. EPA 600/2-82-100.

Kadlec, J.A., and W.A. Wentz. 1974. State-of-the-Art Survey and Evaluation of March Plant Establishment Techniques: Induced and Natural; Vol. 1, Report of Research. Dredged Materials Res. Prog., U.S. Army Corps of Engineers. Contr. Rep. D74-9. 271 pp.

Karathanasis, A.D. 1991. Constructed Wetlands, an Alternative for Wastewater Treatment. Dept. of Agronomy. University of KY. Lexington, KY.

Kepler, D.A. 1990. Wetland Sizing - Design and Treatment Effectiveness. In: J. Skousen, et al, (eds.). Proceedings of the 1990 mining and reclamation conference and exhibition. W. Virginia University, Morgantown, WV. p.403-408.

Kleinmann, R.L.P., et al. 1983. A Low Cost, Low Maintenance Treatment System for Acid Mine Drainage Using Sphagnum Moss and Limestone. Symposium on Surf. Mining, Hydrology, Sedimentology, and Reclamation, Lexington, KY.

Kleinmann, R.L.P., Watzlaf, G.R., and Ackman, T.E. 1985. Treatment of Mine Water to Remove Manganese. Proceedings, 1985 Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation, Graves, D.H., (ed.), Dec. 9-13, 1985, Lexington, KY, pp. 211-217.

Kleinmann, R.L.P., Brooks, R.P., Huntsman, B.E., and Pesavento, B.G. 1986. Constructing Wetlands for the Treatment of Mine Water, Short Course Notes. Presented at the National Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation, Lexington, KY, 53 pp.

Kleinmann, R.L.P., Hedin, R.S., Hyman, D., and Brodie, G.A., 1990. Constructing Wetlands to Treat Acid Mine Drainage. Course Manual for a Workshop Presented at the 1990 National Mining Symposium, Knoxville, Tennessee.

Klusman, R.W. and S.D. Machemer. 1991. Natural Processes of Acidity Reduction and Metal Removal from Acid Mine Drainage. Geology in Coal Resource Utilization. D.C. Peters (ed.). Amer. Assoc. Petroleum Geologists.

Lapakko, K., P. Eger, and J. Strudell. 1986. Low Cost Removal of Trace Metals From Copper-Nickel Mine Stockpile Drainage. Vol. 1, Laboratory and Field Investigations. USBM contract Report J0205047. U.S. Bureau of Mines. Pittsburgh, PA.

Lapakko, K., and P. Eger. 1988. Nickel and Copper Removal From Acid Mine Drainage by a Natural Wetland. IC 9183 Mine Drainage and Surface Mine Reclamation Volume I; Mine Water and Mien Waste. U.S. Bureau of Mines. Pittsburgh, PA. p.301-309.

Lapakko, K., and P. Eger. 1988. Trace Metal Removal From Stockpile Drainage by Peat. IC 9183 Mine Drainage and Surface Mine Reclamation Volume I: Mine Water and Mine Waste. U.S. Bureau of Mines. Pittsburgh, PA. p.291-300.

Laudon, L.S. 1988. Sulfur Mineralization in a Wetland Constructed to Treat Acid Mine Drainage. Master's Thesis No. 3660. Colorado School of Mines, Golden CO.

Lemke, P.R. 1989. Analyses and Optimization of Physical and Hydraulic Properties of Constructed Wetlands Substrates for Passive Treatment of Acid Mine Drainage. Master's Thesis No. 3823. Colorado School of Mines, Golden, CO.

Lyle, E.S., Jr., 1987. Surface Mine Reclamation Manual. Elsevier Science Publ. Co., Inc. New York, NY. 268 pp.

Machemer, S.D., P.R. Lemke, T.R. Wildeman, R.R. Cohen, R.W. Klusman, J.C. Emerick, and E.R. Bates. 1990. Passive Treatment of Metals Mine Drainage Through Use of a Constructed Wetland. In: Proc.16th Ann. Hazardous Waste Research Symp. U.S. EPA Document EPA/600/9-90-037. Cinncinati, OH. p.104-114.

McHerron, L. 1986. Removal of Iron and Manganese from Mine Drainage by Wetlands, Seasonal Effects. Master's Thesis. Penn State Biology Department.

McIntire, P.E., and H. M. Edenborn, 1990. The Use of Bacterial Sulfate Reduction in the Treatment of Drainage From Coal Mines. In: J. Sencindiver, and D. Samuel (eds.). Proc. 1990 Mining & Reclamation Conf. West Virginia Univ. Morgantown, WV.

McIntire, P.E., H. M. Edenborn, and R.W. Hammack. 1990. Incorporation of Bacterial Sulfate Reduction into the Treatment of Acid and Metal Mine Drainage. In: Proc. 1990 National Symposium on Mining. Knoxville, TN. p. 207-213.

Meehan, T. 1991. Personal Communication Regarding the Successful Removal of Mn from Acid Mine Drainage at a Staged Constructed Wetlands in Shade County, PA.

Michaud, S.C. and C.J. Richardson. 1989. Relative Radial Oxygen Loss From Five Wetlands Plants. In: Hammer, D.A. (ed.). Wetlands for Wastewater Treatment. Lewis Publishers, Inc. Chelsea, MI. p. 501-507.

Mitsch, W.J., M.A. Cardamone, J.R. Taylor. 1985. Wetlands and Water Quality Management in the Eastern Interior Coal Basin. pp. 121-137. In: Wetlands and Water Management on Mined Lands: Proceedings of a Conference October 23-24, 1985. The Pennsylvania State University. R.P. Brooks, D.E. Samuel, J.B. Hill (eds.). Pennsylvania State University, University Park, PA.

Nairn, R.W., R.S. Hedin, and G.R. Watzlaf. 1991. A Preliminary Review of the Use of Anoxic Limestone Drains in the Passive Treatment of Acid Mine Drainage. In: Proc. 12th Ann. WV Surface Mine Drainage Task force Symposium, Morgantown, WV.

Nawrot, J.R. and S.C. Yaich. 1982. Wetland Development Potential of Coal Mine Tailings Basins. Wetlands 2:179-180.

Nichols, D.S. 1983. Capacity of Natural Wetlands to Remove Nutrients from Wastewater. J. WPCF, 55(5):495-505.

Oborn, E.T. and J.D. Hem. 1961. Microbiologic Factors in the Solution and Transport of Iron. USGS Water Supply Paper 1459-H.

Oborn, E.T. and J.D. Hem. 1962. Some Effects of the Larger Types of Aquatic Vegetation on Iron Content of Water. USGS Water Supply Paper, 1459-1.

O'Brien, W.S., A.F. Calli, and C.Wen. 1974. Chemical Ionic Equilibrium Relationships Involved in Mine Drainage Neutralization and Treatment. Fifth Symposium on Coal Mine Drainage Research. N.C.A., Louisville, Kentucky.

Pesavento, B.G. 1984. Factors To Be Considered When Constructing Wetlands for Utilization As Biomass Filters To Remove Minerals From Solution. In: Burris, J. E. (ed.). Treatment of Mine Drainage by Wetlands, Contribution #264, Dept. of Biology, The Pennsylvania State University, p. 45.

Puustjarvi, V. 1952. The Precipitation of Iron in Peat Soil. Acta Agr. Fenn. 78:7-72.

Reddy, R.K., and W.H. Smith (eds.). 1987. Aquatic Plants for Resource Recovery. Magnolia Press, Inc. Orlando, FL. 1032pp.

Reed, S.C., Middlebrooks, E.J., and Crites, R.W. 1988. Natural Systems for Waste Management and Treatment, McGraw-Hill Book Co., New York, NY, 308 pp.

Reynolds, J.S, J.L. Bolis, S.D. Machemer, and T.R Wildeman. 1991. Sulfate Reduction in a Constructed Wetland. Environmental Chemistry Vol. 31, No. 1. p.504-509.

Rice, P.A. and F. Rabolini. 1972. Biological Treatment of Acid Mine Water. Fourth Symposium on Coal Mine Drainage Research. Coal Industry Advisory Committee to the Ohio River Valley Water Sanitation Commission, Pittsburgh, PA.

Ristich, S., S. Frederick, and E. Buckley. 1976. Transplantation of Typha and the Distribution of Vegetation and Algae in a Reclaimed Estuarie Marsh. Torrey Bot. Club Bull. 103(4):157-164.

Sanda, A.P., 1989. ProMac Continues to Prove Itself. Coal 26:9.

Seidel, K. 1976. Macrophytes and Water Purification. In: J. Tourbier and R. Pierson (eds.). Biological Control of Water Pollution. University of Pennsylvania Press. Pennsylvania, PA. p.109-122.

Sellstone, C.J. 1990. Sequential Extraction of Fe, Mn, Zn, and Cu from Wetland Substrate Receiving Acid Mine Drainage. Master's Thesis No. 3851. Colorado School of Mines. Golden, CO. 88 pp.

Sencindiver, J.C. and D.K. Bhumbla. 1988. Effects of Cattails (Typha) on Metal Removal from Mine Drainage. Bureau of Mines Information Circular 9183:359-366. Pittsburgh, PA.

Skousen, J., J. Sencindiver and D. Samuel (editors). 1990. Proceedings of the 1990 Mining and Reclamation Conference and Exhibition. 2 volumes. West Virginia University, Morgantown, WV. Contains a number of relevant references.

Snoddy, E.L., Brodie,G.A., Hammer, D.A., and Tomljanovich, D.A. 1989. Control of The Armyworm, Simyra henrici (Lepidoptera: Noctuidae), on Cattail Plantings In Acid Drainage Treatment Wetlands At Widows Creek Steam-Electric Plant. In: Hammer, D.A., (ed.). Wetlands for Wastewater Treatment, Lewis Publishers, Inc., Chelsea, MI, pp. 801-811.

Snyder, C. and E. C. Ajarrah. 1984. The Influence of the Typha Community on Mine Drainage. pp. 149-153. In: Proceedings of 1984 Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation. University of Kentucky, Lexington, KY.

Sobec, A.A., D.A. Benedetti, and V. Rastogi. 1990. Successful Reclamation Using Controlled Release Bactericides. In: J. Skousen, J. Sencindiver, and D. Samuel. Proc. 1990 Mining and Reclam. Conf. WV Univ. Morgantown, WV. p. 33-41.

Spangler, F.L., Wm. E. Sloey, and C. W. Fetter, Jr. 1976. Artificial and Natural Marshes as Wastewater Treatment Systems in Wisconsin. Presented at Freshwater Wetlands and Sewage Effluent Disposal: Ecosystem Impacts, Economics, and Feasibility. University of Michigan.

Spratt, A.K. and R.K. Wieder. 1988. Growth Responses and Iron Uptake in Sphagnum Plants and Their Relation to Acid Mine Drainage Treatment. In: U.S. Bur. of Mines. Mine Drainage and Surface Mine Reclamation. Bureau of Mines Information Circular 9183:279-285.

Stanlick, H.T. 1976. Treatment of Secondary Effluent Using a Pet Bed. pp. 257-268. In: Freshwater Wetlands and Sewage Effluent Disposal. D.L. Tilton, R. W.-Kadlec, and C. J. Richardson (eds.). University of Michigan Press, Ann Arbor, MI.

Stark, L.R., R.L. Kolbash, H.J. Webster, S.E. Stevens, K.A. Dionis, and E.R. Murphy. 1988. The Simco #4 Wetland: Biological Patterns and Performance of a Wetland Receiving Acid Mine Drainage. Bureau of Mines Information Circular 9183:332-344.

Stark, L.R., S.E. Stevens, Jr., H.J. Webster, and W.R. Wenerick. 1990. Iron Loading, Efficiency, and Sizing in a Constructed Wetland Receiving Mine Drainage, 1990. In: Proc. 1990 Mining and Reclamation Conf. WV University. Morgantown, WV. p. 393-401.

S.E. Stevens, Jr., K. Dionis, and L.R. Stark. 1989. Manganese and Iron Encrustration on Green Algae Living in Acid Mine Drainage. In: Hammer, D. A. (Ed). Constructed Wetlands for Wastewater Treatment. Lewis Publishers. Chelsea, MI. p 765-773.

Stone, R.W. 1984. The Presence of Iron and Manganese - Oxidizing Bacteria in Natural and Simulated Bogs. In Burris, Jr., E., (ed.) 1984, Treatment of Mine Drainage by Wetlands, Contribution No. 264 of the Department of Biology, The Pennsylvania University.

Stumm, W. and J. J. Morgan. 1970. Aquatic Chemistry. Wiley Interscience, New York, NY, 583 p.

Sunda, W.G. and Huntsman, S.A. 1988. Effects of Sunlight on Redox Cycles of Manganese in the Southwestern Sargasso Sea. Deep Sea Research, Vol. 35, No. 8, p.1297.

Tarutis, W.J., Jr. and R.F Unz. 1990. Chemical Diagenesis of Iron and Manganese in Constructed Wetlands Receiving Acidic Mine Drainage. In: P.F. Cooper an B.C. Findlater (eds.). Constructed Wetlands in Water Pollution Control. Pergamon Press. Elmsford, NY. p.429-440.

Taylor, H.N., K.D. Choate, and G.A. Brodie. 1992. Storm Event Effects on Constructed Wetlands Discharges. In: G. Moshiri (ed.). Constructed Wetlands for WQ Improvement - Proc. of an Int'l Conf. Lewis Publ., chelsea, MI. In Press.

Tchobanoglous, G. and G.L. Culp. 1980. Wetland Systems for Wastewater Treatment. In: S.C. Reed and R.K. Bastian (eds.) , Aquaculture Systems for Wastewater Treatment: An Engineering Assessment, EPA 430/9-80-007.

Tilton, D.L., R.H. Kadlec, and C.J. Richardson (eds.). 1976. Freshwater Wetlands and Sewage Effluent Disposal. University of Michigan Press, Ann Arbor, MI.

Tourbier, J. and R. W. Pierson, Jr. (eds.). 1976. Biological Control of Water Pollution. University of Pennsylvania Press, Philadelphia, PA.

Turner, D and McCoy, D. 1990. Anoxic Alkaline Treatment System, A Low-Cost Alternative for Treating Acid Mine Drainage. In: D.H. Graves (ed.). National Symposium on Mining Proceedings. Lexington, KY.

Tuttle, M.D. 1988. America's Neighborhood Bats. Univ. of Texas Press, Austin, TX. 96 pp.

U.S. Department of Agriculture. 1982. Ponds-Planning, Design, Construction. Soil Conserv. Serv., Handbook. No. 590, 51 pp.

U.S. Environmental Protection Agency. 1976. Erosion and Sediment Control. EPA-625/3-76-006, Vol. 1, 102 pp., Vol. 2, 137 pp.

U.S. Environmental Protection Agency. 1985. Freshwater Wetlands for Wastewater Management Handbook, EPA 904/9-85-135.

U.S. Environmental Protection Agency. 19856. Practical Guide for Groundwater Sampling.

U.S. Environmental Protection Agency. 1988. Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment. EPA 655/1-88/022, 83 pp.

U.S. EPA - 905/3-84-002. Region 5. Chicago, IL & U.S. Fish & Wildlife Service - Ecological Impacts of Wastewater on Wetlands - 2/84. Available - Region 5 Water Division 200 S. Dearborn, Chicago, IL.

U.S. EPA. 1985. Freshwater Wetlands for Wastewater Management: Environmental Handbook, EPA 904/9-85-135.

U.S. EPA. 1983. Design Manual: Neutralization of Acid Mine Drainage, EPA-600/2-81-001.

U.S. EPA. 1979. Aquaculture Systems for Wastewater Treatment: Seminar Proceedings and Engineering Assessment, EPA 430-9-80-006.

U.S. EPA. 1984. Literature review of wetland evaluation methodologies. Technical Report, NTIS No. PB 85-186922, 120 pp.

U.S. Geological Survey. 1977. National Hardbook of Recommended Methods for Water Data Acquisition. Reston, VA.

Van Everdingen, R.O. and H.R. Krouse. 1988. Interpretation of Isotopic Compositions of Dissolved Sulfates in Acid Mine Drainage. In: Mine Drainage and Surface Mine Reclamation. U.S. Bureau of Mines Info Circular 9183. Pittsburgh, PA. pp. 147-156.

Voight, J.C. and J.R. Cockrell. 1987. Effects of a Wetland on Acid Mine Drainage on the New Diggings Branch. Directed study, Univ. of Wisconsin, Reclamation Program. Platteville, WI.

Warburton, D.B., W.B. Klimstra, and R.J. Nawrot. 1985. Aquatic Macrophyte Propagation and Planting Practices for Wetland Development. In: R.P. Brooks, D.E. Samuel, and J.B. Hill (eds.). Proc. Wetlands and Water Management on Mined Lands Conf. Pennsylvania State University, University Park, PA, p.139-152.

Water Pollution Control Federation. 1990. Natural Systems for Wastewater Treatment. Manual of Practice FD-16. Alexandria, VA. 270pp.

Watzlaf, G.R. 1985. Comparative Tests to Remove Manganese from Acid Mine Drainage. Bureau of Mines Information Circular No. 9027.

Watzlaf, G.R. 1988. Chemical Stability of Manganese and Other Metals in Acid Mine Drainage Sludge. In: Mine Drainage and Surface Mine Reclamation, Volume 1. U.S. Bureau of Mines Info. Circ.9183. p. 83-90.

Wenerick, W.R., S.E. Stevens, Jr., H.J. Webster, L.R. Stark, and E. DeVeau. 1988. Tolerance of Three Wetland Plant Species to Acid Mine Drainage: A Greenhouse Study. In: D.A. Hammer (ed.), Constructed Wetlands for Wastewater Treatment, Lewis Publishers, Chelsea, MI, pp. 801-807.

Whitehouse, A.E., and H.V. Weaver, Jr. 1990. Office of Surface Mining Reclamation and Enforcement, Wetland Policy Update. In: Proc. 12th Annual Abandoned Mined Land Conference. Breckinridge, Co. p.345.

Weider, R.K. 1989. A Survey of Constructed Wetlands for Acid Coal Mine Drainage Treatment in the Eastern United States. Wetlands. Volume 9, number 2. p.299-315.

Wieder, R. K. 1990. Metal Retention in wetlands Constructed for Acid Coal Mine Drainage Treatment. Presented at National Assoc. of Abandoned Mine Lands Programs Conf. Breckinridge, CO.

Weider, R.K.. 1991. The Kentucky Wetlands PRoject: A Field Study To Evaluate Man-Made Wetlands For Acid Coal Mine Drainage Treatment. A Cooperative Agreement (GR-896422). U.S. Bureau of Mines. Pittsburg, PA.

Wieder, R.K., and Lang, G.E. 1984. Influence of Wetlands and Coal Mining on Stream Water Chemistry. Water Air Soil Pollut. Vol. 23, pp. 381-396.

Wieder, R.K. and Lang, G.R. 1986 Fe, Al, Mn, and S Chemistry of Sphagnum Peat in Four Peatlands with Different Metal and Sulfur Input. Water Air and Soil Pollution, Vol. 29, pp. 309-320.

Wieder, R.K., G.E. Lang, and A.E. Whitehouse, 1982. Modification of Acid Mine Drainage in a Freshwater Wetlands. In: McDonald, R. E., (ed.). Proceedings of the Symposium on Wetlands in the Unglaciated Appalachian Region, West Virginia University.

Wieder, R.K., Lang, G.E., and Whitehouse, A.E. 1984. Destruction of a Wetland Ecosystem by Inputs of Circum-neutral, Treated Coal Mine Drainage. In: D. H. Graves (ed.) Int'l Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation, University of Kentucky. Lexington, KY. p.433-441.

Wieder, R.K., G.E. Lang, and A.E. Whitehouse. 1985. Metal Removal in a Sphagnum-Dominated Wetlands. In: Brooks, R.P., et al. (eds.). Wetlands and Water Management on Mined Lands, Proc. of a Conference. The Pennsylvania State University.

Wieder, R.K., M. Linton, and K. Heston. 1990. Laboratory Mesocosm Studies of Fe, Al, Mn, Ca, and Mg Retention in Wetlands Exposed to Synthetic Acid Coal Mine Drainage. Water, Air, and Soil Pollution. 51:181.

Wildeman, T. R. 1990. Passive Treatment of Metals Through Use of a Constructed Wetland: Evaluation of Operation. Presented at the National Assoc. of Abandoned Mined Lands Programs Conference. Breckinridge, CO.

Wildeman, T.R., S.D. Machemer, R.W. Klusman, R.R. Cohen, and P.R. Lemke. 1990. Metal Removal Efficiencies from Acid Mine Drainage in the Big Five Tunnel Constructed Wetland. In: J. Skousen, J. Sencindiver, and D. Samuel (eds.). Proc. 1990 Mining and Reclam. Conf. WV Univ. Morgantown, WV pp. 417-424.

Wildeman, T.R., J. Gusek, and G.A. Brodie. 1991. Wetland Design for Mining Operations. Manual for a Short Course Presented at the 8th National Meeting ASSMR. Durango, CO.

Witthar, S.R. 1989. Wetland Design for the Treatment of Acid Mine Drainage. Proc. 11th Annual Assoc. of Abandoned Mine Land Programs Conference. Williamsburg, VA.