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# *Engineering Bulletin*
# Constructed Wetlands Treatment

## PURPOSE

This engineering bulletin summarizes recent information to help remedial project managers, on-scene coordinators, contractors, and other site cleanup managers understand the type of data and site characteristics needed to evaluate a technology for potential applicability to Superfund or other hazardous waste sites. Section 121(b) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) requires the United States Environmental Protection Agency (EPA) to select remedies that "utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable" and to prefer remedial actions in which treatment "permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances, pollutants, and contaminants as a principal element." This bulletin reviews the use of constructed wetlands for treating aqueous metal contamination at mining and other hazardous waste sites. However, this is a developing technology and technical opinions regarding the design and operation of constructed wetlands systems are diverse.

## Technology Applicability

Constructed wetlands have been demonstrated effective in removing organic, metal, and nutrient elements including nitrogen and phosphorus from municipal wastewaters, mine drainage, industrial effluents, and agricultural runoff. The technology is waste stream-specific, requiring characterization of all organic and inorganic constituents. The need for cost-effective and efficient treatment of municipal wastewater in rural areas of the United States resulted in the development of several constructed wetlands for sewage treatment. The processes and techniques used in constructed wetland treatment of municipal wastewater have been well developed and are discussed in several recent texts (EPA 1988a, Reed et al. 1995, Hammer 1989, Cooper and Findlater 1990, and Moshiri 1993). However, literature discussing the use of constructed wetlands to treat metal-contaminated waste streams such as mine drainage is not as readily available. This engineering bulletin discusses the use of constructed wetlands treatment of metals-contaminated waste streams and provides performance data from recent case studies.

In general, the development of constructed wetland technology in the United States has focused on the remediation of coal mine and metal mine drainages. The United States Bureau of Mines and the Tennessee Valley Authority (TVA) have conducted considerable research in developing the constructed wetland technology to treat coal mine drainages. The Bureau of Mines research is summarized in Special Information Circular 9389 (1994) and the TVA results are contained in various publications including Hammer (1989) and Moshiri (1993). Metal mine applications have been developed by the Colorado School of Mines, the State of Minnesota, the State of Colorado (Division of Minerals and Geology), and others. Further, several investigators (for example, Staub and Cohen 1992, Eger 1992) have used bioreactors to treat mine drainage, based on extension of the constructed wetlands technology.

The chemistry of contaminated coal mine drainages in the eastern United States is dominated by elevated levels of iron and sulfate resulting from the weathering of pyrite ($FeS_2$) exposed by mining activities. At neutral pH, $FeS_2$ oxidizes when exposed to air (autoxidation) to form dissolved iron and sulfuric acid. Below a pH of 4.0, auto-oxidation reaction rates slow dramatically; however, pyrite oxidation can be maintained by bacterial action. *Thiobacillus thiooxidans* can oxidize sulfur from pyrite by reaction 1 (autoxidation occurs in the same way).

(1) $2\,FeS_2 + 7\,O_2 + 2\,H_2O \rightarrow 2\,Fe^{2+} + 4\,SO_4^{=} + 4\,H^+$

*Thiobacillus ferrooxidans* can oxidize the aqueous ferrous iron produced in reaction 1 to ferric iron by reaction 2.

(2) $4\,Fe^{2+} + O_2 + 4\,H^+ \rightarrow 4\,Fe^{3+} + 2\,H_2O$

Ferric iron produced in this reaction can react with sulfide ions to regenerate ferrous iron (reaction 3) or may form an insoluble hydroxide ($Fe(OH)_3$) and precipitate (reaction 4).

(3) $8\,Fe^{3+} + S^{=} + 4\,H_2O \rightarrow 8\,Fe^{2+} + SO_4^{=} + 8\,H^+$

*[reference number, page number

(4) $2\ Fe^{3+} + 6\ H_2O \rightarrow 2\ Fe(OH)_3 + 6\ H^+$

The overall reaction for the oxidation of pyrite is the sum of reactions 1, 2 and 4 (reaction 5).

(5) $4\ FeS_2 + 15\ O_2 + 14\ H_2O \rightarrow 4\ Fe(OH)_3 + 16\ H^+ + 8\ SO_4^=$

As indicated by equation 5, pyrite weathering contributes a large amount of iron and acidity (low pH) to coal mine drainage. Moreover, aerobic wetlands used in the remediation of coal mine discharge typically treat water containing high levels (50 to 500 milligrams per liter [mg/L]) of iron and low-to-moderate pH (4 to 7). Figure 1 provides cross sections of both aerobic and anaerobic constructed wetlands showing the primary metal removal mechanisms active in each system. In aerobic wetlands, the iron is removed primarily by oxidation followed by precipitation of iron hydroxides (equations 2 and 4) or jarosite, an amorphous iron sulfate.

The removal of metals by anaerobic constructed wetlands is a complex combination of chemical precipitation, sorptive and biologically mediated precipitation processes. In general, sulfate-reducing bacteria within the wetlands produce hydrogen sulfide that reacts with dissolved metals to form insoluble and slightly soluble metal sulfides. The metal sulfides precipitate from the aqueous solution and are filtered out by the solid material (substrate) that makes up the wetland. The substrate material's ability to support sulfate-reducing bacteria and filter out the metal sulfides is important to the effectiveness of the anaerobic constructed wetland.

Table 1 shows the effectiveness of constructed wetland technology on general contaminant groups for waters. Examples of constituents within the contaminant groups are provided in the *Technology Screening Guide For Treatment of CERCLA Soils and Sludges* (EPA 1988b). However, performance data presented in this bulletin may not be directly applicable to all mining or Superfund sites. Numerous variables including the type of contamination, concentration of contaminants, alkalinity within the mine drainage, site climate, and topography will affect the performance of the constructed wetland systems. A thorough characterization of the contaminant waste stream through chemical analysis and aqueous geochemical modeling is highly recommended. In addition, a well designed and conducted treatability study is also recommended.

## Technology Description

Constructed wetlands vary in size and complexity depending on the wastewater stream to be treated, the capacity required, and the required level of remediation. There are generally three types of constructed wetlands: free-water surface systems (FWS), subsurface flow systems (SF), and aquatic plant systems (APS) (EPA 1988a). An FWS wetland (Figure 1 top) typically consists of shallow basins or channels with slow flowing water and plant life. An SF wetland (Figure 1 bottom) typically consists of basins or channels filled with a permeable substrate material which the water flows through rather than over as in an FWS. An APS is essentially an FWS with somewhat deeper channels containing floating or suspended plants such as water hyacinths or microorganisms such as algae. The different types of wetlands can be used alone, in combination, or with other remediation technologies to address a variety of treatment needs.

In general, FWS and APS are aerobic wetlands that remove metals primarily by aerobic oxidation of iron followed by precipitation of iron hydroxides, which leads to the removal of other metals. In addition, anaerobic removal of some metals may occur in the deeper zones of the FWS and APS wetlands. FWS and APS wetlands are most successful in removing iron, manganese, arsenic, and selenium from mine drainage with moderately low to neutral pH (Gusek et al. 1994). Iron is removed as a hydroxide or jarosite as previously described. Arsenic and selenium are believed to sorb to the iron hydroxide as it precipitates and settles out. Manganese is slowly removed as an oxide after the iron has precipitated and the hydrogen ion concentration lowered to nearly neutral conditions (Hedin et al. 1994). Liming or the addition of alkalinity to the water through an anoxic limestone drain prior to the FWS hastens the formation of iron hydroxides and manganese oxides. Aquatic plants and microorganisms may also consume acidity (equation 6) of APS waters through photosynthetic activity with similar results.

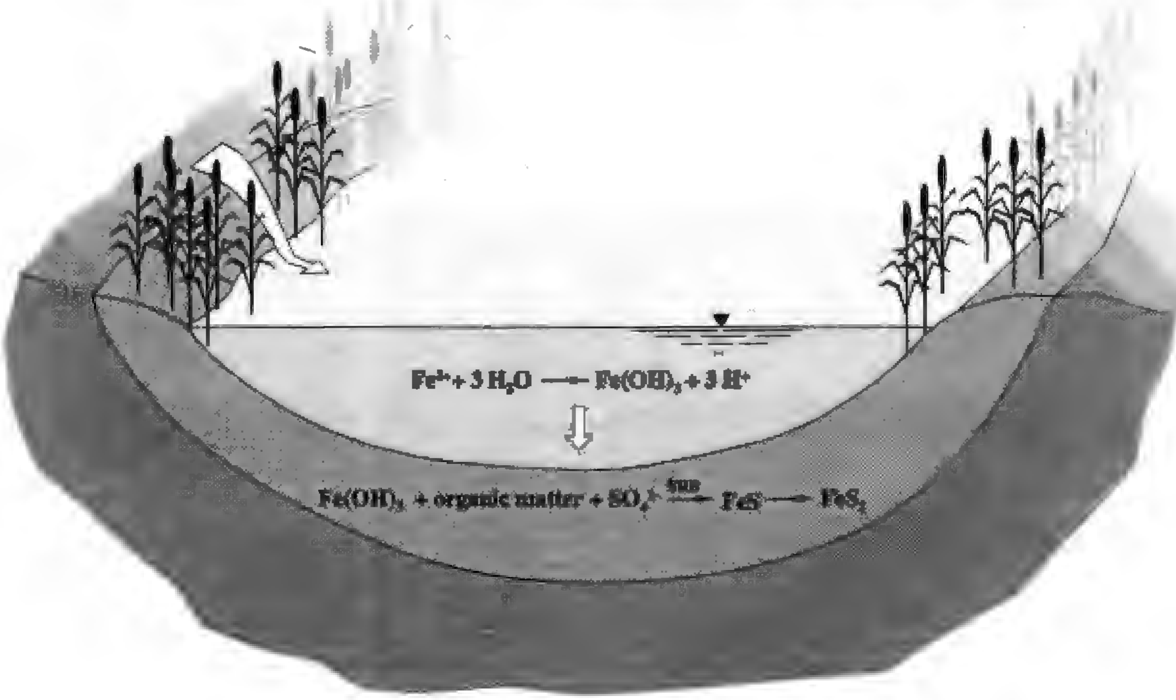
(6) $106\ CO_2 + 16\ NO_3^- + HPO_4^= + 122\ H_2O + 18\ H^+ \xrightarrow{light} C_{106}H_{263}O_{110}N_{16}P + 138\ O_2$

Lowering the hydrogen ion concentration to a pH of 9.5 or greater substantially increases the manganese oxidation rate, thus enhancing manganese removal from most mine drainages (Bureau of Mines 1985).

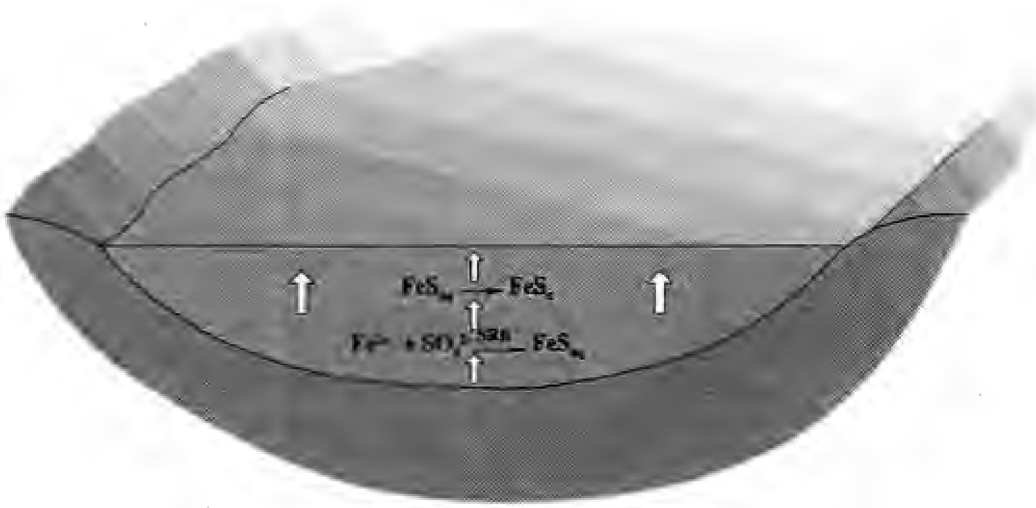
Figure 2 provides a general schematic of a staged wetland system that may include plants. The various types of cells depicted in Figure 2 can be used in a variety of combinations to achieve the necessary treatment. This FWS design proposed by TVA consists of basins with a natural or constructed subsurface barrier of clay or impervious geotechnical material (Brodie 1993). The system shown in Figure 2 uses an anoxic limestone drain with deep and shallow ponds, marshes, a rock filter, and an alkaline bed (usually limestone) to remediate coal mine drainage. As previously mentioned, the limestone drain increases the alkalinity of the mine drainage, thereby enhancing iron hydroxide precipitation in the deep pond and deep marsh. The increased alkalinity and loss of iron allow manganese oxides to form with removal by precipitation. Additional manganese is removed in the rock filter by adsorption to the rock and absorption by algae growing on the rock surfaces. Finally, pH is adjusted to regulatory levels by chemical amendment in the alkaline bed followed by total suspended solids (TSS) removal in the polishing cell. The various cells shown in Figure 2 can be used in any combination to meet site-specific treatment requirements.

SF wetlands are anaerobic systems that vary significantly in size and complexity. Figure 3 presents a simple peat wetland system constructed in an existing drainage (Frostman 1993). A series of SF wetland cells was created by simply constructing a series of berms and using peat as a substrate material. Limestone beds (Figure 3) can be used in conjunction with SF constructed wetlands to increase the alkalinity, and induce

## FIGURE 1: AQUATIC CHEMISTRY OF WETLAND SYSTEMS




AEROBIC SYSTEM




ANAEROBIC UPFLOW SYSTEM

⇨ Flow Direction

SRB Sulfate Reducing Bacteria

aq Aqueous

s Solid

**TABLE 1**

**CONSTRUCTED WETLAND SYSTEM TREATMENT EFFECTIVENESS**

| Contaminant Groups | | Water |
|---|---|---|
| Organic Compounds | Halogenated volatile compounds | ▲ |
| | Halogenated semivolatile compounds | ▲ |
| | Nonhalogenated volatile compounds | □ |
| | Nonhalogenated semivolatile compounds | □ |
| | PCBs | ▲ |
| | Pesticides | ▲ |
| | Dioxins and furans | □ |
| | Organic cyanides | ▲ |
| | Organic corrosives | □ |
| Inorganic Compounds | Volatile metals | ■ |
| | Nonvolatile metals | ■ |
| | Asbestos | □ |
| | Radioactive materials | ▲ |
| | Inorganic corrosives | □ |
| | Inorganic cyanides | □ |
| Reactive Compounds | Oxidizers | ▲ |
| | Reducers | □ |

Notes:

□ No expected effectiveness: expert opinion that technology will not work.

▲ Potential effectiveness: expert opinion that technology will work.

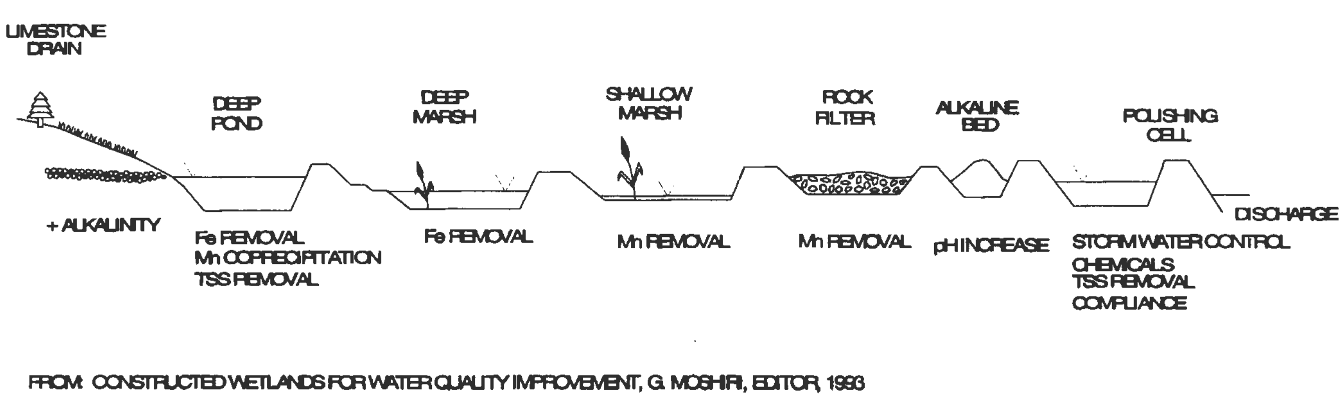
■ Demonstrated effectiveness: successful treatability test completed at some scale.

some precipitation of metal hydroxides before the waste stream enters the wetland. However, aluminum, iron, zinc, and copper in acid mine drainage tend to create an exterior "armor" on the surface of limestone beds exposed to air or dissolved oxygen; thereby reducing the limestone's ability to dissolve. Although Figure 3 depicts a wetland utilizing peat as the substrate material, peat has a limited sorption capacity, contains few nutrients, and may not always be readily available.

Figure 4 depicts a highly engineered SF wetland cell that includes a linear flow distribution system that is being evaluated by EPA for high altitude applications. Additional information about this system is provided in the performance data section of this bulletin. This type of wetland cell or reactor would be relatively expensive to construct compared with other types; however, it may be the most effective wetland in cold climates. Even with the high construction costs, this type of wetland may be more cost-effective than traditional treatment.

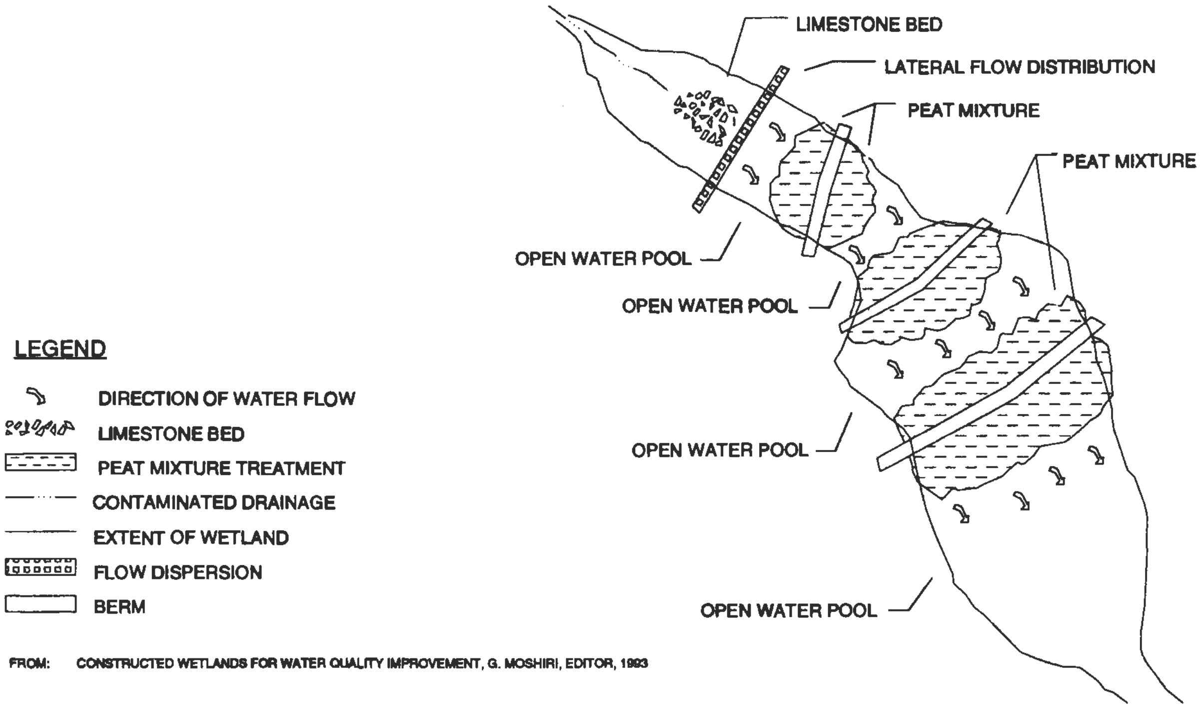
One of the more critical components of an SF is the organic-rich substrate placed in the wetland cell. The substrate provides a source of carbon and essential nutrients (nitrogen and phosphorus) for the wetland microorganisms. In addition, the substrate must be able to filter the metal sulfides as they precipitate from the wetland porewater. Several types of substrate materials have been used in a variety of mixtures including depleted mushroom compost, peat moss, aged manure, decomposed wood products, limestone, topsoil, and straw (EPA 1993). Several recent investigations have used substrate mixtures of fresh compost and alfalfa hay with considerable success (EPA 1993, Staub and Cohen 1992). Bench-scale or pilot-scale testing of readily available substrate components may be required to determine the most appropriate substrate mixture for site-specific conditions.

**FIGURE 2: GENERAL SCHEMATIC OF STAGED AEROBIC CONSTRUCTED WETLANDS**



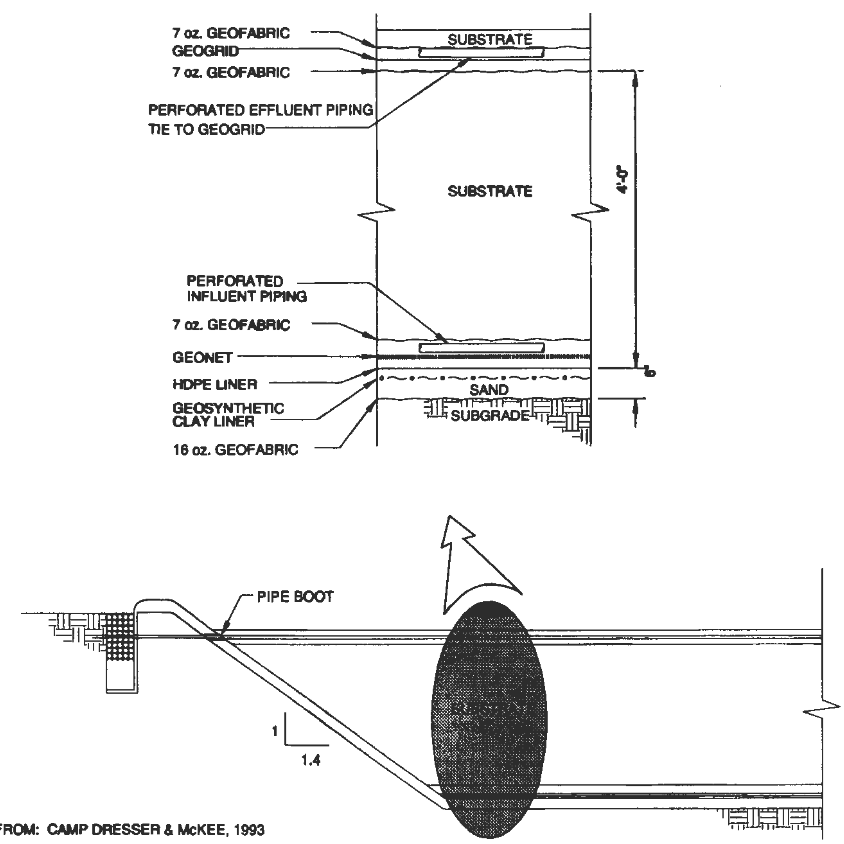

FROM: CONSTRUCTED WETLANDS FOR WATER QUALITY IMPROVEMENT, G. MOSHIRI, EDITOR, 1993

## FIGURE 3: TYPICAL PEAT/WETLAND TREATMENT SYSTEM




FROM: CONSTRUCTED WETLANDS FOR WATER QUALITY IMPROVEMENT, G. MOSHIRI, EDITOR, 1993

## FIGURE 4: SCHEMATIC CONSTRUCTION DETAIL OF AN UPFLOW SF WETLAND CELL




FROM: CAMP DRESSER & McKEE, 1993

**TABLE 2**

**ANAEROBIC CONSTRUCTED WETLANDS SYSTEM**
**METAL SULFIDE FORMATION AND SOLUBILITY PRODUCT DATA**

| Element | Sulfide | $\Delta F_f^o$ (kcal) | Solubility Product |
|---|---|---|---|
| Ag | $Ag_2S$ | -9.36 | $1x10^{-50}$ |
| Al | $Al_2S_3$ | -117.7 | ND |
| Cd | CdS | -33.6 | $1x10^{-27}$ |
| Co | CoS | -19.8 | $7x10^{-23}$ |
| Cr | NF | NA | NA |
| Cu | $Cu_2S$ | -20.6 | $3x10^{-49}$ |
| Fe | FeS | -23.3 | $8x10^{-19}$ |
| Hg | HgS | -11.7 | $2x10^{-53}$ |
| Mg | MgS | ND | ND |
| Mn | MnS | -49.9 | $3x10^{-14}$ |
| Mo | $MoS_2$ | -53.8 | ND |
| Ni | NiS | -17.7 | $3x10^{-21}$ |
| Pb | PbS | -22.2 | $3x10^{-28}$ |
| Zn | ZnS | -47.7 | $2x10^{-25}$ |

Notes:

$\Delta F_f^o$ Formation constant (from the elements) from Garrels and Christ 1990
NF Not formed
NA Not applicable
ND No data

In general, SF wetlands are anaerobic systems that remove metal contaminants by reaction with hydrogen sulfide produced by sulfate-reducing bacteria forming insoluble metal sulfides. Table 2 provides metal sulfide formation (from the elements) and solubility product data for common mine drainage metal contaminants. The more negative the formation constant, the stronger the tendency for the metal sulfide to form. The data indicate that all of these metals readily form a metal sulfide, with the exception of chromium. Aluminum, cadmium, iron, manganese, molybdenum, and zinc have the strongest tendencies to form sulfides; however, the aluminum sulfide decomposes in aqueous environments. Solubility product data indicate the strong tendency of the metal and the sulfide ion to precipitate from aqueous solution. However, solubility product determinations do not consider metal complexation and their use may result in misleading precipitation or solubility predictions. For example, the solubility products of HgS and PbS differ by 25 orders of magnitude, but their aqueous solubilities may be quite similar (Stumm and Morgan 1981). For these reasons, the use of an aqueous geochemical model, such as MINTEQA2, to evaluate metal speciation and complexation is encouraged. In addition, potential metal removal with SF wetlands can be modeled with MINTEQAK, a program designed for aerobic and anaerobic wetland modeling (Klusman 1993).

The flow scheme of SF wetlands is simple. The treatment stream may first flow through a bed of crushed limestone to increase alkalinity and induce some metals oxidation and precipitation. The drainage then flows into the wetland cell where it flows through the substrate. Depending on the cell design, the drainage can flow either vertically up or down or horizontally through the substrate. Within the substrate, inorganic contaminants are sorbed, precipitated, or biologically reduced and precipitated. The treated water then flows out of the cell where it may flow into another cell or polishing pond. Generally, residence times of 50 to 100 hours have been used successfully in SF wetlands. Maintaining proper flow of the mine drainage through the substrate may require frequent adjustment.

## Performance Data

This section provides performance results for several constructed wetlands previously evaluated or currently being evaluated. One of the first wetlands constructed to treat acid mine drainage was the SIMCO wetland (Coshocton County, Ohio) completed in 1985. The SIMCO wetland consists of four cells separated by small ponds followed by three larger settling ponds. The total area of the system is 4,138 square meters ($m^2$) and is planted with cattails (*Typha latifolia*). The wetland cells are composed of 15 centimeters (cm) of crushed limestone overlain with 45 cm of spent mushroom compost. Evaluation of the SIMCO wetland conducted by researchers from Pennsylvania State University indicated removal efficiency has steadily increased over the 8 years of operation (Stark et al. 1994). Iron removal efficiencies in 1985 were approximately 20 to 50 percent, and between 1991 and 1993 ranged from 70 to 100 percent. Detailed manganese removal data have not been presented; however, a comparison of mean influent and effluent manganese concentrations suggests manganese is not removed by the SIMCO constructed wetland.

Between 1984 and 1993, the Bureau of Mines monitored 13 constructed wetlands designed to treat coal mine drainage. The results of the monitoring are discussed in detail by Hedin et al. (1994). These systems include constructed wetlands in combination with anoxic limestone drains, retention ponds, and modified ditches. In addition, a variety of substrate materials was evaluated and cattails was the most common vegetation used during the studies. The studies determined dilution is an important process within these systems and must be determined to accurately evaluate metal removal rates. The results also indicate alkalinity in the mine drainage improves the wetlands removal of iron. For example, iron removal averaged 53 percent in the effluent from the third cell of the Latrobe wetland (0 alkalinity in drainage) while iron removal in effluent samples collected from the Donegal wetland averaged 85 percent. The influent to the Donegal wetland contained 202 mg/L of alkalinity and both wetlands contained substrates of limestone and spent mushroom compost. Finally, the studies suggest oxygen transfer is the limiting process in iron removal (oxidation and precipitation) in these constructed wetland systems.

TVA constructed 14 wetland systems for treating drainage at coal mining facilities. Impoundment 1 (IMP1) is one of 12 TVA operational wetlands and was constructed at the Fabius coal processing plant in 1985. IMP1 contains four aerobic cells and covers 5,700 $m^2$. The influent water has a pH of 3.1, iron concentration of 69 mg/L, and manganese concentration of 9.3 mg/L. Effluent water from IMP1 constructed wetlands contains 0.9 mg/L of iron, 1.8 mg/L of manganese, and a pH of 6.7. Originally, five species were planted at IMP1 including broadleaf cattail (*Typha latifolia*), wool grass (*Scirpus cyperinus*), rush (*Juncus effusus*), scouring rush (*Equisetum hyemale*), and squarestem spikerush (*Eleocharis quandrangulata*). Today, more than 70 species have been identified in IMP1 with the broadleaf cattail, wool grass, rush, spike rush, and rice cutgrass (*Leersia oryzoides*) the dominant plant life. In addition, the original stream draining the area contained fewer than five invertebrate species. Presently, the stream contains more than 30 invertebrate species (Brodie 1993) and several minnow species.

The EPA Superfund Innovative Technology Evaluation (SITE) Program is evaluating (demonstrating) upflow and downflow SF wetlands at the Burleigh Tunnel, Silver Plume, Colorado. The demonstration resulted from the successful operation and testing of an earlier system at the Big 5 Tunnel (Idaho Springs, Colorado) within the SITE Emerging Technology Program (EPA 1993). The mine drainage from the Burleigh Tunnel contains elevated levels of zinc (45 to 90 mg/L) at a neutral pH. Table 3 presents data for both cells through the first 12 months of operation. The data for the first year indicate the upflow cell consistently removes better than 99 percent of the zinc contamination in summer and fall, and the removal efficiency reduces to 70 percent in the winter. The downflow cell removed 70 to 85 percent during the first year. In addition, results of 48-hour acute toxicity testing with fathead minnows (*pimephales promelas*) and *Ceriodaphnia dubia* indicate both cells are removing the toxicity of the mine drainage. The demonstration of the SF constructed wetland at the Burleigh Tunnel continued through August 1995.

## Technology Status

Currently, there are several hundred constructed and natural wetlands treating coal mine drainage in the eastern United States. The effectiveness of these systems is discussed in several publications including Hammer (1989), Moshiri (1993), the proceedings of annual meetings of the American Surface Mining and Reclamation Association, and United States Bureau of Mines papers (United States Bureau of Mines Special Publication SP066-94 and Hedin et al. 1994).

In addition, many constructed wetlands designed to treat metal mine drainages have been built and tested or are being tested by EPA, various state agencies, and industry. In Colorado, the State Division of Minerals and Geology has built several constructed wetland systems to treat mine drainage. In Pennsylvania, the Department of Environmental Resources completed a best professional judgment analysis for seeps from coal mine operations and determined constructed wetlands were the best available technology for the treatment of alkaline or mildly acidic waters (Hellier et al. 1994). Finally, constructed wetlands treatment is being considered for the full-scale remedy of the Burleigh Tunnel drainage.

A state-of-the-art, pilot-scale wetland has been constructed at the Wheal Jane mine in the Cornwall area of southern England. The drainage from the Wheal Jane abandoned tin mine contains elevated levels of cadmium, zinc, arsenic, and iron. The design of the Wheal Jane constructed wetland is similar to the staged system shown in Figure 2. The system begins with an anoxic pond followed by an anoxic drain, then an aerobic cell, followed by an anaerobic cell, and lastly a rock filter. Both the anoxic limestone drain and the anaerobic cell use earthen covers to prevent oxygenated rainwater from entering these cells. The Wheal Jane wetland has begun a 2-year performance evaluation period.

EPA has recently completed a wetland database that includes location, system, permit, cell design, performance, reports, and personnel information for 178 municipal wetland sites (EPA 1994).

**TABLE 3**

**BURLEIGH TUNNEL CONSTRUCTED WETLANDS**
**SITE DEMONSTRATION RESULTS**
**AVERAGE ZINC CONCENTRATIONS (mg/L) IN 1994 AND 1995**

| | March | April | May | June | July | Aug | Sept | Oct | Nov | Dec | Jan | Feb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Influent | 56.7 | 62.0 | 50.4 | 49.6 | 58.0 | 56.1 | 57.0 | 56.5 | 62.9 | 63.0 | 56.3 | 58.0 |
| Effluent Upflow | 0.16 | 0.28 | 0.23 | 0.24 | 0.24 | 0.48 | 1.1 | 2.8 | 6.8 | 9.0 | 12.1 | 17.4 |
| Downflow | 9.7 | 15.4 | 11.5 | 10.1 | 15.9 | 14.9 | 16.4 | 14.8 | 12.1 | 8.8 | 9.0 | 11.1 |

## Limitations

Constructed wetland systems typically have extensive land requirements compared to conventional treatment systems. Thus, in areas with high land values, a constructed wetland treatment system may not be appropriate. Land available relatively close to the source of contaminated water is preferable to avoid extended transport of contaminated water. Land that is relatively level facilitates the construction of wetlands, while locations with steep slopes and drainages will make construction more difficult, costly, and potentially unsafe.

The climate of potential constructed wetland sites can limit the effectiveness and operation of the system. Extended periods of severe cold, extreme hot and arid conditions, and frequent severe storms or flooding may result in operational and performance problems. Extreme cold can freeze a wetland and substantially reduce the microbial population, rendering it ineffective for an extended period after thawing. The large water surface areas and plant life associated with wetlands enhance evaporation and evapotranspiration. A constructed wetland may periodically dry up at a site with low water flow rates in a hot and arid location. If the wetland is not designed for cyclical periods of wet and dry, it may be less effective during the wet periods. Constructing wetlands in areas with frequent flooding or severe storms can lead to washout of substrate materials or exposure of the microorganisms to toxic levels of metal contamination. Extensive engineering controls to overcome climatic or geographic limitations may eliminate the cost and maintenance advantages that make constructed wetlands attractive.

Contaminant types and concentrations in the treatment stream can be limiting factors for constructed wetland system applications. High concentrations of contaminants may shorten the effective life of a constructed wetland, which have a limited life based on the volume of the wetland or the amount of organic substrate placed in the wetland. Substrate limitations include the number of sites for adsorption of inorganic contaminants and the amount of organic nutrients for biological activity. The wetland is no longer effective once the sites are full and the organic matter is exhausted. At this point, the wetland must be dredged to remove the spent substrate. High concentrations of suspended solids in the treatment stream may also reduce the life of a constructed wetland. Suspended solids fill aerobic wetlands and the substrate pore spaces, reducing permeability and preventing flow through the treatment system in anaerobic systems.

## Cost

In general, there are no typical unit costs of constructed wetlands due to site-specific conditions and treatment requirements. The extent of engineering and construction required will dramatically affect the cost. The costs associated with FWS wetlands typically used to treat coal mine drainages are calculated per area while costs for SF wetlands are based on volume. Costs and cost considerations for constructing various wetlands are reported in the literature (EPA 1988a, Hammer 1989, Moshiri 1993, EPA 1993).

An example of the variable wetland costs was reported as \$3.58/m$^2$ to \$32.08/m$^2$ of wetland in a study of constructed wetlands for acid mine drainage treatment by TVA (Brodie 1988). A cost study of eastern wetlands for treating drainages at coal mines conducted by the United States Bureau of Mines indicated an average cost of approximately \$10.00/m$^2$ of wetland (Kleinmann 1995). Construction costs of the pilot-scale SF wetland at the Burleigh Tunnel, Silver Plume, Colorado were estimated to be \$570 per cubic meter. Note that this cost is based on wetland volume. This SF is a highly engineered system with multilayer liners; sophisticated piping, distribution, and collection systems; and a customized substrate material designed to operate year-round at high altitude (9,150 feet above mean sea level).

Constructing wetlands involves common construction techniques and materials which make development of a construction cost estimate straightforward. Operation and maintenance costs are comparatively small compared to traditional treatment systems. One cost that is often overlooked is the cost of replacing and disposing of the spent substrate (SF) or dredging and disposal of bottom sediment (FWS). The disposal costs can be significant if the substrate or sediment is allowed to become a hazardous waste due to high metal concentrations. The cost of spent substrate or sediment disposal may be offset by metal recovery from the material. If low-cost, level land is available, constructed wetlands could be an economical treatment method when compared with other treatment options.

In conclusion, constructed wetlands treatment appears to be effective in removing metals from and toxicity in aqueous waste streams. Construction materials used to build these systems are inexpensive and readily available. Compared to other metal treatment technologies, constructed wetlands may be a cost-effective alternative.

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