TECHNOLOGY OVERVIEW

CONSTRUCTED TREATMENT WETLAND

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Prepared by
The Interstate Technology & Regulatory Council
Mining Waste Team

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CONSTRUCTED TEATMENT WETLAND

1. INTRODUCTION

Constructed treatment wetlands are man-made biologically active systems such as bogs, swamps, or marshes that are characterized by saturated soil conditions and at least periodic surface or near-surface water designed specifically to treat contaminants in surface water, groundwater, or waste streams. The purpose of this section is to provide an overview of technical and regulatory guidance (ITRC 2003) to help regulators, industry, consultants, and technology vendors understand, evaluate, and make informed decisions about the use of constructed treatment wetland systems as they may pertain specifically to the treatment of mining-influenced water (MIW).

Constructed treatment wetlands combine the abiotic and biotic functions of natural wetlands to reduce or eliminate waterborne contaminants associated with MIW. In some cases, constructed treatment wetlands are used as a containment option to confine solid wastes, such as process waste. Constructed treatment wetlands can be designed in a number of different ways and can include aerobic wetlands, anaerobic horizontal-flow wetlands, and vertical-flow ponds (vertical-flow wetlands). The main difference in these systems is the biological and chemical processes promoted and the design of water flow direction. Aerobic wetlands are typically designed to precipitate metals in water under aerobic conditions, usually in a horizontal-flow system. Anaerobic horizontal-flow wetlands treat water under anaerobic conditions through the use of a carbon substrate and typically move water horizontally. Vertical-flow wetlands move the impacted water vertically through carbon substrate over a limestone bed (Demchak, Morrow, and Skousen 2001). Basic design information can be found in ITRC's guidance document *Technical and Regulatory Guidance Document for Constructed Treatment Wetlands* (ITRC 2003). Detailed design information can be found in a number of publications, including *Treatment Wetlands*, 2nd ed. (Kadlec and Wallace 2009).

While there is extensive published literature on the subject, constructed treatment wetland applications have generally been limited to the treatment of storm water and municipal wastewaters. However, this technology is now a valid treatment option for a variety of waste streams, including MIW, remedial wastewaters, agriculture waste streams, and industrial waste streams. Constructed treatment wetlands have also been used for "wet capping" of solid wastes. These "wet caps" are often referred to as "capped mine wastes in a wetlands setting." Constructed treatment wetlands can be used in conjunction with other technologies to extend the operational lifespan of the systems or enhance the removal performance of specific constituents of concern. This flexibility makes the technology applicable to many types of contaminants in many types of situations.

The fundamental mechanisms of wetland contaminant removal, overall wetland functions, and degradation mechanisms are described in more detail in *Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised* (ITRC 2009) and *Technical and Regulatory Guidance Document for Constructed Treatment Wetlands* (ITRC 2003). Simply stated, the technology is mature and tested and it is now being used in new applications.

2. APPLICABILITY

Constructed treatment wetlands technologies designed for MIW are applicable to the following:

- high or low volumes of material
- surface water or daylighted groundwater (seeps)
- dissolved and solid phase contaminants
- high-sulfate and low-pH (acidic) waters

Furthermore, these wetlands can be placed in remote, rural, or urban locations; used alone or in combination with other technologies; or used as a solo technology or in conjunction with other technologies

The most common form of MIW contains metal sulfides, which are unstable in the presence of air and can react to release dissolved metals and sulfuric acid. Although water that has contacted waste rock, tailings, or mine workings typically causes the most problems, water that is associated with processing of the ore or from the disturbance of near-surface rock during construction activities can also be problematic. The water quality of mine drainage is a function of rock chemistry and mineralogy, but it typically contains trace metals, iron, manganese, aluminum, and sulfate. Typical concentration ranges for both coal and sulfide ore metal mine drainage are shown in Table 2-1.

Table 2-1. Typical characteristics of mine drainage water

	Coal mine drainage		**Metal mine drainage**	
	Net acid	**Net alkaline**	**Net acid**	**Net alkaline**
pH	3–4	6.5–7.5	3–4	6.5–7.5
Acidity	100–10,000	<0	100–10,000	<0
Sulfate	1,000–10,000	100–3,000	1,000–10,000	100–3,000
Iron, total	10–1,000	<10–100	10–1,000	<10
Aluminum	10–1,000	<1	1–100	<1
Manganese	5–100	<30	2–25	<2
Copper	ND–1	ND	1–100	0.1–1
Zinc	ND–5	ND	10–1,000	1–10
Cadmium	ND	ND	0.05–1	0.01–0.1
Lead	ND	ND	0.5–10	0.01–0.1

Note: Except for pH, all concentrations are in milligrams per liter (mg/L).

Metals found in MIW are site specific and can vary significantly depending on the type of exposed minerals. Those listed in Table 2-1 are fairly common (e.g., copper and zinc) or are of particular concern due to their toxicity (e.g., cadmium and lead). Iron, aluminum, and manganese are the major metals of concern in coal mine drainage although other metals can be present. A potential concern that is frequently overlooked is surface or near-surface rock that is exposed during routine excavation activities such as the construction of roads or other structures requiring the removal of cover material, which leads to the exposure of susceptible materials to air and water. Metal contamination of soils and waters around the world has a severe impact on human health and the environment. Industrial and mining wastes are the most important sources of heavy metal environmental pollution (Quek, Wase, and Forster 1998).

As reported by Hedin, Nairn, and Kleinmann (1994) and Sobolewski (1997, 1999), metal removal processes occurring in wetlands can involve the following series of mechanisms:

- filtration of solids
- sorption onto organic matter
- oxidation and hydrolysis
- formation of carbonates
- formation of insoluble sulfides
- binding to iron and manganese oxides
- reduction to nonmobile forms by bacterial activity
- biological methylation and volatilization of mercury

Constructed treatment wetlands are a long-term, semipermanent technology that can be used alone or in conjunction with other technologies to address both acidity and dissolved metals found in MIW. The technology cannot be considered a permanent solution as the wetlands will eventually be filled with metal-laden sediment that will require ultimate removal or capping. Depending on the initial design, available space, and contaminant loading, constructed treatment wetlands can meet remedial objectives with minimal maintenance for a number of years.

Often wetland performance is judged by removal efficiency, which is the effluent contaminant concentration divided by the influent concentration. It should be noted that this value can sometimes be a misleading figure. High removal efficiencies may indicate a high influent concentration with a much reduced effluent concentration; but low removal efficiencies do not necessarily indicate diminished performance, and this should be taken into account.

Typical removal efficiencies for common mining influenced water parameters are summarized in Table 2-2.

Table 2-2 Typical range of removal efficiencies observed in wetlands constructed to treat mine drainage

Parameter	**Typical removal efficiencies**	
	Coal mine drainage	**Metal mine drainage**
pH	>6	>6
Acidity	75–90%	75–90%
Sulfate	10–30%	10–30%
Iron	80–90+%	80–90+%
Aluminum	90+%	90+%
Copper	NM	80–90+%
Zinc	NM	75–90+%
Cadmium	NM	75–90+%
Lead	NM	80–90+%

Note: NM denotes not measured.

Since wetland treatment is to a large degree a biological process, the time required for treatment may not be acceptable when compared to other technologies, such as chemical precipitation. Removal efficiency is typically a function of treatment time or the hydraulic retention time of the wetland; therefore, constructed wetlands may require large areas to meet the requisite cleanup objective.

3. ADVANTAGES

Constructed treatment wetlands provide a remedial option that, once constructed, can operate for long periods of time with minimal operations and maintenance. Additional advantages include the following:

- Can operate with low or no energy input.
- Potentially applicable in remote locations without utility access.
- Decreased air and water emissions as well as secondary wastes.
- Control of soil erosion, surface water runoff, infiltration, and fugitive dust emissions.
- High design flexibility provides capability to remediate sites with multiple or mixed contaminants.
- Habitat creation or restoration provides land reclamation upon completion.
- Favorable public perception, increased aesthetics, and lower noise than mechanical systems.
- Increasing regulatory acceptance and standardization.
- Carbon dioxide and greenhouse gas sequestration

Most metals can be effectively retained in wetlands through a series of physical, chemical, and biological processes. Sustainable metal uptake occurs primarily in the wetland sediments.

Because the removal or remedial efficiency of constructed treatment wetlands is typically governed by residence time, with excess capacity engineered into the systems, these systems can operate at various flow rates with minimal or no impact on effluent quality and no operator input. Although they should not be considered a “turn on and forget” technology, they can operate in remote locations or situations where constant monitoring or maintenance is impractical.

4. LIMITATIONS

Limitations that may impact the selection of a constructed treatment wetland as a preferred remedial option include the following:

- large remedial footprint per unit treated
    - requires appropriate land for wetlands construction
    - high initial construction cost
- the concentration of contaminants
    - must be monitored to maintain ecological health of the system
    - requires ultimate disposal of accumulated material

- periodic major maintenance
- sensitivity to high throughput excursions
- disposal of accumulated material
- appropriate land must be available for wetlands construction
- relatively slow performance in comparison to other treatment technologies
- dependency on local climatic conditions which may lead to reduced efficiency during colder seasons
- potential to become a permanent feature of the ecosystem, requiring long-term maintenance
- potential to become a mosquito breeding ground; however, this problem is preventable through proper consideration during design
- disagreeable odors associated with natural biological functions which could arise due to anaerobic conditions. Proper design and control of organic loading rates reduces the potential for problem odors.

Wetlands can also add contaminants to water flowing through them; background concentrations of nitrogen, phosphorous, biological oxygen demand, and other water quality parameters are not zero. Thus, removal efficiencies are sometimes negative for some chemicals. This factor must be considered in cases where effluent limits are very stringent, although regulators may be willing to negotiate some permit limits in the case of wetland treatment.

In addition, through the U.S. Environmental Protection Agency's Environmental Technology Initiative, a work group referred to as the Treatment Wetland Policy and Permitting Team issued a report (USEPA 1997) identifying 13 issues pertinent to constructed treatment wetlands. Among the topics addressed in the report are water quality and biological criteria; placement relative to "waters of the United States"; design, construction, and operation and maintenance; and whether treatment wetlands should be used as mitigation wetlands.

5. PERFORMANCE

Over a thousand wetlands have been built to treat mine drainage and range in size from less than an acre to over a thousand acres. Table 5-1 presents information and performance data on several wetlands that were used to treat mine drainage containing different metals.

Table 5-1. Reported removal efficiencies from case studies collected in ITRC's *Technical and Regulatory Guidance for Constructed Treatment Wetlands* (ITRC 2003)

Site name	Metal	Initial (mg/L)	Final (mg/L)	Treatment system
Coal mine drainage, Cagle, TN	Fe	100	2	Anoxic limestone drain prior to surface flow wetland
Rising Star Mine, Shasta County, CA	Cd	0.07–0.47	0.01–0.30	Subsurface, vertical flow; compost substrate overlying limestone gravel
Dunka Mine, Babbitt, MN	Ni	1.5–5.5	0.2–1.5	Surface flow wetlands, peat substrate

Table 5-2 presents examples of metals removal efficiencies from case studies presented in ITRC's 2002 *Constructed Treatment Wetlands* guidance document.

Table 5-2. Examples of metals removal efficiencies from case studies presented in ITRC's *Technical and Regulatory Guidance for Constructed Treatment Wetlands* (ITRC 2003)

Metal	Removal mechanism	Removal %	Case study	Reference
Al	• Oxidation and hydrolysis	33	AMD Wetland, Kentucky (Fabius IMP1)	Edwards 1993
		13	AMD Wetland, Kentucky (Widows Creek)	
	• Formation of insoluble sulfides • Filtration of solids and colloids	75.9	Cypress-gum swamp receiving municipal effluent, Conway, SC	CH2M Hill 1991
As	• Formation of insoluble sulfides • Binding to iron and manganese oxides	70 to +90		Mattes, Gould, and Duncan 2002
Cd	• Formation of insoluble sulfides • Filtration of solids and colloids	98.7	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		75	Bulrushes in gravel	Sinicrope et al. 1992
		79	SSF wetlands	
		99.7	SF cattail	Noller, Woods, and Ross 1994
Cr	• Reduction to nonmobile form by bacterial activity	87.5	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		40	Freshwater marsh receiving urban storm water, Orlando, FL	Schiffer 1989
		84	Bulrushes in gravel	Sinicrope et al. 1992
		68	SSF wetland	
		>65	Retention basin, bulrush SF cells, hydrosoils supplemented w/gypsum	Nelson et al. 2002, Gladden et al. 2003
Cu	• Sorption onto organic matter • Formation of insoluble sulfides • Binding to iron and manganese oxides • Reduction to non-mobile form by bacterial activity	96	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		87.5	Freshwater marsh receiving urban storm water, Orlando, FL	Schiffer 1989
		70.1	Carolina bay receiving municipal effluent, Myrtle Beach, SC	CH2M Hill 1992
		88	SSF Wetland	Sinicrope et al. 1992
		36	Typha SF	
Fe	• Oxidation and hydrolysis • Formation of carbonates • Binding to iron and manganese oxides	66.7	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		58.2	Average for 137-AMD constructed wetlands	Wieder 1989
		98	AMD wetland, KY (Fabius IMP1)	Edwards 1993
		97	AMD wetland, KY (Widows Creek)	
		9	Natural wetland, TN	
Hg	• Sorption to organics/ silts with possible immobilization as sulfides	85 whole system, 75 wetlands	Constructed wetland: storm water retention basin and 8-acre bulrush wetland cells; hydrosols supplemented w/gypsum	Nelson et al. 2002, Gladden et al. 2003

Metal	Removal mechanism	Removal %	Case study	Reference
Mn	• Oxidation and hydrolysis • Formation of carbonates • Binding to iron and manganese oxides	43	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		79	AMD wetland, KY (Fabius IMP1)	Edwards 1993
		40	Natural wetland, TN	
		98	Typha SF	Noller, Woods, and Ross 1994
		75	Typha/Melaleuca SF	
Ni	• Sorption onto organic matter • Formation of carbonates • Binding to iron and manganese oxides	70.7	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		25	Freshwater marsh receiving urban storm water, Orlando, FL	Schiffer 1989
		47	Carolina bay receiving municipal effluent, Myrtle Beach, SC	CH2M Hill 1992
		63	Bulrushes in gravel	Sinicrope et al. 1992
		90	Typha/Melaleuca SF	Noller, Woods, and Ross 1994
Pb	• Formation of insoluble sulfides • Filtration of solids and colloids • Binding to iron and manganese oxides	83.3	Freshwater marsh receiving urban storm water, Orlando, FL	Schiffer 1989
		26	AMD wetland, KY (Widows Creek)	Edwards 1993
		86	Bulrushes in gravel	Sinicrope et al. 1992
		98	Typha SF	Noller, Woods, and Ross 1994
		94	Typha/Melaleuca SF	
Se	• Reduction to non-mobile form by bacterial activity • Volatilization	-		Adriano 2001
Ag ☐	• Formation of insoluble sulfides • Filtration of solids and colloids	89.5	Cypress-gum swamp receiving municipal effluent, Conway, SC	CH2M Hill 1991
Zn	• Formation of insoluble sulfides • Filtration of solids and colloids • Binding to manganese oxides	66.7	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		73	Freshwater marsh receiving urban storm water, Orlando, FL	Schiffer 1989
		33	Carolina bay receiving municipal effluent, Myrtle Beach, SC	CH2M Hill 1992
		79	AMD wetland, KY(Widows Creek)	Edwards 1993
		96	Bulrushes in gravel	Sinicrope et al. 1992
		98	Typha/Melaleuca SF	Noller, Woods, and Ross 1994

6. COSTS

In many cases, one of the greatest advantages of constructed treatment wetlands is their low operations and maintenance cost. The total cost of constructed treatment wetlands is based on a number of parameters but is usually quantified as a unit cost for construction plus the cost per unit volume treated for operations and maintenance. Constructed treatment wetlands are primarily built to treat contaminated water or to contain the movement of solids, not to replace or mitigate habitat lost through development; however, constructed treatment wetlands can offer valuable habitat and prevent adverse runoff in many situations. Where possible, the value of the habitat should be considered among net benefits when constructing any wetland.

Under Remediation Technologies Screening Matrix and Reference Guide, information is included regarding some cost analysis (http://www.frtr.gov/matrix2/section4/4-43.html).

Construction of a wetland can generally be considered a heavy earth-moving project, and unless a synthetic liner is required, construction costs (other than substrate, vegetation, and specialty influent and effluent structures) will be similar in scope and costs to the construction of a storm water retention system.

7. REGULATORY CONSIDERATIONS

Almost all wetlands constructed for the remediation of mining influenced water do provide some level of treatment, but they may not always provide consistent compliance. At some sites, however, for example at abandoned mine sites in remote locations, complete regulatory compliance may not be necessary to improve water quality and restore aquatic life to the impacted receiving waters.

Federal, state, tribal, and/or local regulations, in addition to those listed below, may be applicable. Coordination with appropriate agencies on projects is usually required, and, when appropriate, cooperative and collaborative planning and information-sharing sessions with community and business representatives, environmental groups, regulatory agencies, and the general public may also be necessary. A list of potentially application federal rules and regulations follows:

- Clean Water Act and "Waters of the U.S."
- Clean Water Act Section 303, Water Quality Standards
- Clean Water Act Section 401, Certification
- Clean Water Act Section 402, National Pollutant Discharge Elimination System (NPDES) Program
- Clean Water Act Section 404, Discharge of Dredged or Fill Material (e.g., rock, sand, and soil) to waters of the U.S.
- Other Federal Legal and Programmatic Considerations
  - Clean Water Act Section 319 (Nonpoint Source Pollution Program)
  - Estuary management plans under Clean Water Act Section 320
  - Coastal Zone Management Act, including Reauthorization Amendments of 1990
  - Endangered Species Act
  - Fish and Wildlife Coordination Act
  - Magnuson-Stevens Fishery Conservation and Management Act
  - Migratory Bird Treaty Act
  - National Environmental Policy Act
  - National Wild and Scenic Rivers Act
  - National Historic Preservation Act

8. STAKEHOLDER CONSIDERATIONS

Since constructed wetlands are man-made ecosystems that include permanent or semipermanent structures that can have a long-term esthetic impact, it is important to take into account both the fate and transport of the contaminants as well as the siting, operation, and maintenance of the system. Since these systems concentrate contaminants, care should be taken to isolate and manage constructed treatment wetlands to protect human health and the environment.

Constructed treatment wetlands should generally be constructed on uplands, outside waters of the U.S., and outside of floodplains or floodways in order to avoid damage to natural wetlands and other aquatic resources. Because constructed treatment wetlands can be influenced by natural hydraulic cycles, placement should include consideration of factors such as flood control, hydraulic routing, flood damage potential, and wetland hydrology. (For more information on waters of the U.S., see USEPA 2000, Section VII.A and Appendix I, and Executive Order 11988, *Floodplain Management*).

9. LESSONS LEARNED

Over a thousand wetlands have been built to treat mine drainage ranging in size from less than an acre to over a thousand acres. Although the technology is still being developed due to ongoing improvements in understanding the biology and chemistry of the systems, there is a general understanding of the basic components and processes involved with using constructed treatment wetlands for the removal of contaminants associated with mining influenced water. The removal efficiency of constructed treatment wetlands varies substantially from about 10% to over 99%. This extreme range indicates that these systems are very site specific and that the design, construction, operation, and maintenance of these systems must be done by qualified individuals.

10. CASE STUDIES

Table 10-1. Case studies using constructed treatment wetlands

Bark Camp, PA
Commerce/Mayer, OK
Copper Basin, TN
Keystone, CA
Hartshorne/Whitlock, OK
Lab Bench Test, PA
Ohio Multiple Sites, southeast OH
Tecumseh-AML Site 262, IN
Valzinco Mine, Spotsylvania County, VA

11. REFERENCES

Adriano, D. C. 2001. *Trace Elements in Terrestrial Environments: Biogeochemistry, Bioavailability, and Risk of Metals*, 2nd ed. New York: Springer.

CH2M Hill. 1991. *Grand Strand Water and Sewer Authority Central Wastewater Treatment Plant Wetlands Discharge*. Central Slough Pilot Study Fifth Annual Report, July 1990–June 1991. Prepared for Grand Strand Water Sewer Authority.

CH2M Hill. 1992. *Carolina Bay Natural Land Treatment Program.* Final Report. Prepared for Grand Strand Water and Sewer Authority.

Demchak, J., T. Morrow, and J. Skousen. 2001. "Treatment of Acid Mine Drainage by Four Vertical Flow Wetlands in Pennsylvania," *Geochemistry: Exploration, Environment, Analysis*, **1**(1): 71–80.

Edwards, M. E. 1993. Unpublished data from Tennessee Valley Authority.

Gladden, J. B., E. A. Nelson, W. L. Specht, J. A. Bowers, T. H. Harris, S. M. Harmon, and J. H. Rodgers. 2003. Presentation at the Southeast Environmental Management Association, Augusta, GA, April 23.

Hedin, R. S., R. W. Nairn, and R. L. P. Kleinmann. 1994. *The Passive Treatment of Coal Mine Drainage.* U.S. Bureau of Mines Information Circular 9389.

Hendrey, G. R., J. Clinton, K. Blumer, and K. Lewin. 1979. *Lowland Recharge Project Operations Physical, Chemical, and Biological Changes 1975–1978.* Final report to the Town of Brookhaven, Brookhaven National Laboratory, Brookhaven, NY.

ITRC (Interstate Technology & Regulatory Council). 2003. *Technical and Regulatory Guidance Document for Constructed Treatment Wetlands.* WTLND-1 Washington, DC: Interstate Technology & Regulatory Council, Wetlands Team. www.itrcweb.org.

ITRC. 2004. *Making the Case for Ecological Enhancements.* ECO-1. Washington, DC: Interstate Technology & Regulatory Council, Alternative Landfill Covers, Constructed Treatment Wetlands, and Phytotechnology Teams and the Wildlife Habitat Council. www.itrcweb.org.

ITRC. 2005. *Characterization, Design, Construction, and Monitoring of Mitigation Wetlands.* WTLND-2. Washington, DC: Interstate Technology & Regulatory Council, Mitigation Wetlands Team. www.itrcweb.org.

ITRC. 2006. *Planning and Promoting Ecological Land Use of Remediated Sites.* ECO-2. Washington, DC: Interstate Technology & Regulatory Council, Ecological Land Reuse Team. www.itrcweb.org.

ITRC. 2009. *Technical and Regulatory Guidance Document and Decision Trees for Phytotechnology, Revised.* PHYTO-3. Washington, DC: Interstate Technology & Regulatory Council, Phytotechnologies Team. www.itrcweb.org.

Kadlec, R. H., and S. Wallace. 2009. *Treatment Wetlands*, 2nd ed. Boca Raton, FL: CRC Press.

Nelson, E. A., W. L. Specht, J. A. Bowers, and J. B. Gladden. 2003. "Constructed Wetlands for Removal of Heavy Metals from NPDES Outfall Effluent," pp. 13–21 in *Proceedings, 2002 National Conference on Environmental Science and Technology*, G. Uzochukwu et al., eds. Columbus: Battelle Press.

Noller, B. N., P. H. Woods, and B. J. Ross, 1994, "Case Studies of Wetland Filtration of Mine Waste Water in Constructed and Naturally Occurring Systems in Northern Australia," *Water Science and Technology* **29**: 257–66.

"Ore Hill Mine Reclamation Project (CERCLA)." n.d. U.S. Forest Service. http://www.fs.usda.gov/detail/whitemountain/landmanagement/projects/?cid=stelprdb5209639.

Quek, S., D. Wase, and C. F. Forster. 1998. "The Use of Sago Waste for the Sorption of Lead and Copper," *Water SA* **24**(3): 251–56.

Schiffer, D. M. 1989. "Water Quality Variability in a Central Florida Wetland Receiving Highway Runoff," *Water: Laws and Management,* F. E. Davis. ed. Bethesda, MD: American Water Research Association.

Sinicrope, T. L., R. Langis, R. M. Gersberg, M. J. Busanardo, and J. B. Zedler. 1992. "Metal Removal by Wetland Mesocosms Subjected to Different Hydroperiods," *Ecological Engineering* **1**(4): 309–22.

Sobolewski, A. 1997. "The Capacity of Natural Wetlands to Ameliorate Water Quality: A Review of Case Studies," pp. 1551–63 in *Proceedings, 4th International Conference on Acid Rock Drainage,* vol. 4. Vancouver, B.C., Canada.

Sobolewski, A. 1999. "A Review of Processes Responsible for Metal Removal in Wetlands Treating Contaminated Mine Drainage," *International Journal of Phytoremediation* **1**(1): 19–51.

Wieder, R. K. 1989. "A Survey of Constructed Wetlands for Acid Coal Mine Drainage Treatment in the Eastern United States," *Wetlands* **9**: 299–315.

USEPA (U.S. Environmental Protection Agency). 1997. *Wetlands for Water Quality Management and Habitat Enhancement: Policy and Permitting Issues*. Final ETI Report. Prepared by the Environmental Technology Initiative (ETI) Wetland Policy Team and CH2M Hill for the Office of Wastewater Management, U.S. Bureau of Reclamation, and the City of Phoenix.

USEPA 2000. *Guiding Principles for Constructed Treatment Wetlands: Providing for Water Quality and Wildlife Habitat*. EPA 843-B-00-003. Washington, DC: Office of Wetlands, Oceans, and Watersheds.

USEPA. 2004. *Wetland Banking at Former Mine Lands: An Ecological Solution with Economic Benefits.* USEPA Fact Sheet. Superfund Program, Abandoned Mine Lands.