unrepaired may lead to dike failure. A thick layer of sand or gravel on the fill or wire screening inhibits burrowing. If burrowing damage continues, aggressive trapping, hunting, and poisoning may be necessary in accordance with federal, state, and local regulations.

In summary, an initial maintenance program that includes frequent and thorough inspection and immediate correction of problems is critical to ensuring successful operation of wastewater treatment wetlands.

REFERENCES

1. "Ponds—Planning, Design and Construction," Agricultural Handbook No. 590, USDA, Soil Conservation Service (July 1982).
2. "Landscape Design: Ponds," Landscape Architecture Note 2, USDA, Soil Conservation Service (September 1988).
3. "Ponds and Reservoirs," in *Engineering Field Manual for Conservation Practices,* rev. ed., USDA, Soil Conservation Service (1989), ch. 11.
4. "Water Quality Field Guide," SCS-TP-160, USDA, Soil Conservation Service (September 1983).
5. "National Food Security Act Manual," Title 180-V-NFSAM, USDA, Soil Conservation Service (March 1988).
6. Boon, A. G. "Report of a Visit by Members and Staff of WRC to Germany to Investigate the Root-Zone Method for Treatment of Wastewaters," Water Research Centre, Stevenage, England (August 1985).
7. Watson, J. T., and J. A. Hobson. "Hydraulic Design Considerations and Control Structures for Constructed Wetlands for Wastewater Treatment," Chapter 30, this volume.

CHAPTER 33

Considerations and Techniques for Vegetation Establishment in Constructed Wetlands

Hollis H. Allen, Gary J. Pierce, and Rex Van Wormer

Construction of wetlands has received increasing interest over the last 15 or 20 years, particularly for development of wildlife and fisheries habitat on dredged material,[1-3] erosion control of coastal and reservoir shorelines,[4,5] wastewater treatment,[6] and other purposes, such as mitigation of highway impacts.[7] This chapter describes considerations and techniques learned from experience in developing wetlands for wastewater treatment. It focuses on herbaceous macrophytes because most of what is known about wastewater treatment with wetlands concerns these types of plants. It also focuses primarily on in situ substrates, in contrast to substrates borrowed from other areas.

FACTORS INFLUENCING WETLAND ESTABLISHMENT

Three important factors contribute to the diversity of natural wetlands and form the basis for any wetland development protocol. These are (1) hydrologic considerations, (2) substrate, and (3) vegetation. Within the context of this chapter, "hydrology" also includes water quality. Variations in hydrology and substrate have a particularly strong influence on vegetative diversity. Through an understanding of the relation between these factors, it is possible to determine which species should be planted, and by what means, under given environmental conditions.

Hydrologic Considerations

Water depth and frequency of flooding or its periodicity are important in determining the plant species appropriate to a constructed system. Water depth causes different vegetation zones in a wetland in part because deeper water may restrict oxygen from reaching the substrate.[8] Water depth may also influence the degree of light penetration and photosynthesis.

Periodicity, duration, and seasonality of flooding are important for selecting plant species to be used for wetlands development. Wetland plants can withstand various degrees of flooding depending on when and for how long the flooding occurs. Many wetland emergent plants need a period of lower water level during the growing season, whereas in the dormant season, drawdown is not as important.

Water quality factors affecting selection of wetland plant species include such factors as water clarity, pH, salt concentration, and dissolved oxygen. Degree of water clarity is considered the most important, particularly for submerged aquatics. If water is stained or turbid, light penetration will be reduced and limit photosynthesis. Under these conditions, rooted aquatics having a floating growth form and habit should be selected for use.

Salt concentration either within the water column or the substrate has a major influence on plant species selection. In saline environments, species such as smooth cordgrass *(Spartina alterniflora)* or salt grass *(Distichlis spicata)* or some other such saltwater species may be selected. Salt tolerance levels have been determined for many plants.[2]

Substrate

Many substrates are suitable for wetland establishment. Loamy soils are especially good because they are soft and friable, allowing for easy rhizome and root penetration. But fine-textured soils such as clays may limit root and rhizome penetration. Low nutrient content may limit growth and development as may excessive nutrients (i.e., calcium levels that exceed the adaptive range of particular species). However, substrates with low nutrient concentrations may be suitable in constructed wetlands for wastewater treatment if other requirements are met, because of nutrient-enriched influent. Usually, soil amendments are not necessary in wetlands for plant growth because hydrophytes grow well in a broad range of soil types, but where a limitation exists amendments may enhance success. Specifications for wetland construction frequently call for placement of a layer of wetland or upland topsoil. Although little experimental evidence demonstrates benefits from this practice, it will probably continue because of its perception as beneficial. Evidence from a New York project suggested that drying and aerating a wetland soil is especially good for wetlands establishment because such soils have high levels of nutrients and oxidation followed by flooding enhanced macronutrient availability.[9]

Although peaty organic soils support wetland plants, they are not preferred for wetland development. They are low in nutrients because organic acids, yielding many hydrogen ions, occupy cation exchange sites, and once flooded they have a loose, soft texture that provides inadequate support for emergent aquatics. In such soils, it might be necessary to anchor each planting unit individually.

Substrates should be evaluated for calcium content. Many wetland plants such as sago pondweed (*Potamogeton pectinatus*), and muskgrass *(Chara* spp.) are known calcifiles, while others are known to be restricted to acid soils

(e.g., *Sphagnum* spp.). Many species have a broad tolerance for calcium levels and can be planted in a diversity of soils; for example, softstem bulrush *(Scirpus validus)* and pickerelweed *(Pontederia cordata)* tolerate high calcium levels. In marsh construction at the Tompkins County, New York airport, wetlands with abundant calcium carbonate became dominated by muskgrass *(Chara* sp.), despite planting a variety of species.

Site excavation for wetland establishment is likely to expose a subsoil that may not be as conducive to plant growth as the topsoil. Clays and gravels frequently underlying more favorable soils may be sufficiently dense or hard to inhibit root penetration, may lack nutrients found in topsoil, or may be impermeable to water needed by roots. Emerson[10] hypothesized that establishment of a planted wetland in New York was limited by dense soils that inhibited plant growth. In a South Carolina wetland planting,[11] plants could survive in heavy clay soil, but their spread was limited to the original planting hole. However, a clay layer below the root zone is often essential to retain water.

Sandy, coarse textured, and subsoil substrates often lack nutrients and may require fertilizer.[4] However, sandy soils hold plants well and prevent them from floating out of the planting surface, in contrast to peaty or silty soils. Planting in sand media can be efficient and inexpensive because of ideal texture for hand planting; however, sand or gravel will dry out quickly and may need irrigation if water levels cannot be maintained at the root level.

Nutrient conditions in constructed wetlands are improved by natural processes and by horticultural techniques. Conversion from aerobic conditions to anaerobic conditions in a constructed wetland results in a major conversion of oxidized iron (Fe^{3+}) to reduced iron (Fe^{2+}). Subsequently, phosphorus availability changes because it is more soluble when associated with reduced iron. Potassium is also readily available in flooded soils, although the mechanism for its availability is more complex. Nitrogen, lost through nitrification in aerobic soils, is retained in wetland soils and is not usually limiting whenever organic material is present. Consequently, some researchers do not consider macronutrients limiting in aquatic systems newly constructed from upland areas.[12]

Little is known about nutrient requirements of individual hydrophytes, and consequently general fertility concepts are often applied. In coastal salt marshes, coarse-textured soils and subsoils frequently are nutrient-poor[3] and require fertilization. Water-soluble fertilizers and broadcast fertilization have obvious disadvantages in flooded wetland systems, where such applications would be highly mobile. Side dressing with time-release fertilizers, low in solubility, is frequently used to overcome this difficulty.[3] Osmocote and Mag-amp are granular, slow-release formulations of inorganic fertilizer appropriate to wetland plantings.[3] When water covers the plantings and cannot be lowered, fertilizer is applied through the water column, making granular formulations difficult to apply. To overcome this problem, Agriform tablets have been used successfully in a 12-ha planting in South Carolina.[11] In nutrient-enriched situations, fertilization may still be necessary until plants become well established.

Vegetation

The vegetative component is a major factor in successful wetland development. Which plants will grow given the hydrological and substrate conditions in the developed wetland? Which plants provide the appropriate attributes for wastewater treatment? How are the plants to be selected? For wastewater treatment, plants selected should (1) be active vegetative colonizers with spreading rhizome systems; (2) have considerable biomass or stem densities to achieve maximum translocation of water and assimilation of nutrients;[13] (3) have maximum surface area for microbial populations; (4) have efficient oxygen transport into the anaerobic root zone to facilitate oxidation of reduced toxic metals[14] and support a large rhizosphere; and (5) be a combination of species that will provide coverage over the broadest spread of water depths envisioned for the terrain conditions. One must couple the above attributes with the hydrologic and substrate conditions in choosing species for planting.

It is important to understand how a particular species might react to given wetland conditions before that species is nominated for use in a wetland development project. Wetland plants use a number of adaptive strategies to withstand varying edaphic and hydrologic conditions. Many strategies are unique to wetland plants or to particular wetland conditions. For example, wetland plants have air spaces (aerenchyma) in roots and stems that allow the diffusion of oxygen from the aerial portions of the plant into the roots.[15] In practice, an empirical evaluation by simply selecting species growing under conditions similar to the habitat to be developed may be the most successful.

As mentioned earlier, water depth dictates zonation of wetland plants, and species should be selected primarily on this criterion. This is more easily done by thinking in terms of planting zones. Based on the authors' experience, these zones are defined with reference to the normal water level (0.0 cm) and are divided into *deep* (-91 to -152 cm); *mid* (-15 to -91 cm); *shallow* (-15 to +15 cm); and *transitional* (+15 to +45 cm) (Figure 1). Although other wetland plants may thrive at different depths or elevations than those portrayed (Figure 1), this classification can be adopted as a general model for a broad hydrological regime for wetlands development.

SOURCES OF PLANT MATERIALS

Wetland plants can be purchased from nurseries, collected in the wild, or grown for a specific project. Each method has distinct advantages and disadvantages regarding quality of material, availability of plants, and cost for acquisition and planting. No generalization can be made which would recommend any particular source for all projects. However, the authors agree that for most projects, wild collected material is most desirable for reasons discussed below.

Only a few commercial nurseries specialize in wetland plants for wetland

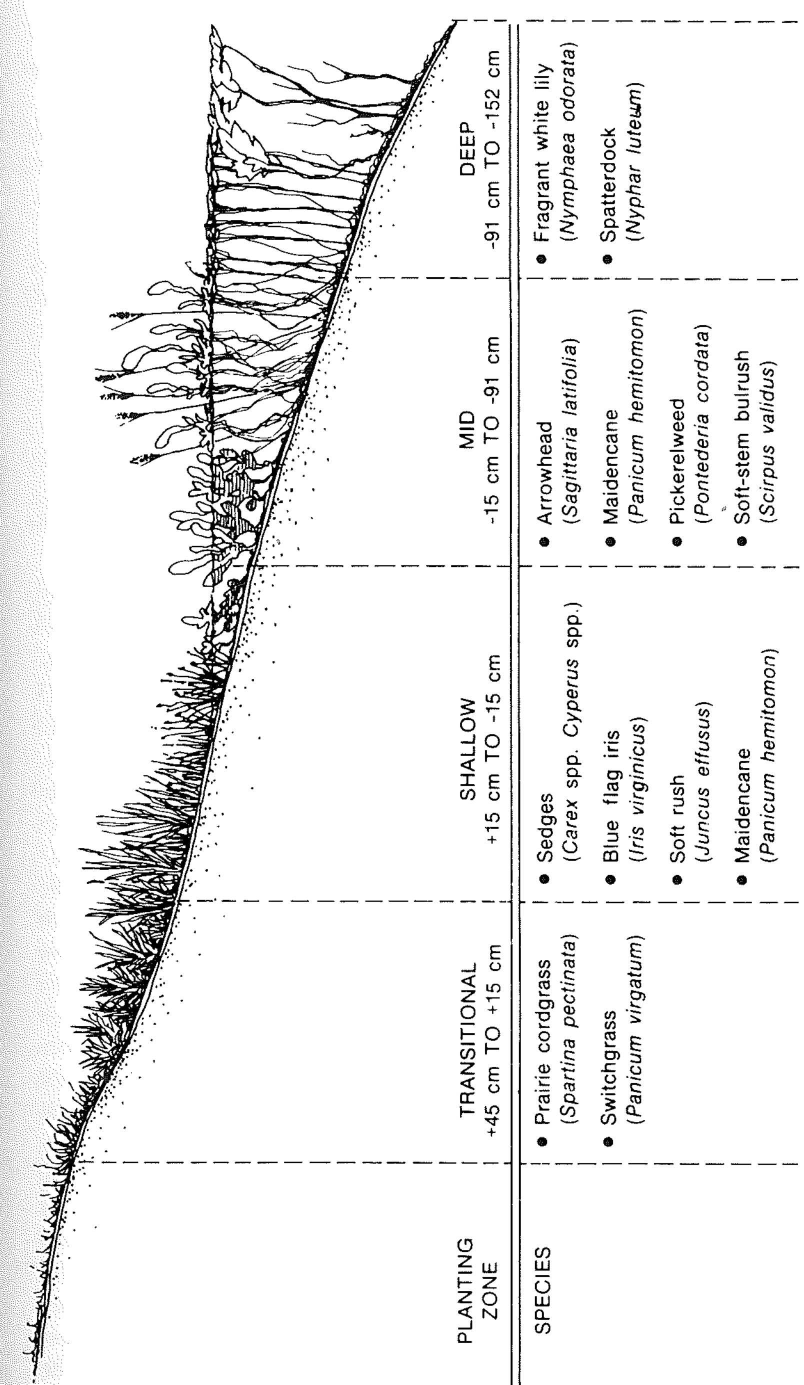

Figure 1. Typical interior United States wetland plants by planting zone, as they are related to normal water level (0.0 cm).

construction. Most can be found in Florida, Maryland, New York, and Wisconsin with almost none in the central and western United States. Other sources include state nurseries, commercial tree and shrub nurseries, seed companies, and suppliers of native flower and landscaping plants. Regional lists of dealers in plants for conservation plantings are available from the Soil Conservation Service, and these lists are invaluable for obtaining wetland adapted species.

Plants obtained from wetland nurseries are supplied in different forms. Potted materials are available from at least one nursery. These are relatively expensive, averaging $1.00 or more per plant. Other suppliers offer bare-root seedlings collected from outdoor beds and stored under refrigeration. These are typically $0.25 or less per seedling. Freshly collected growing plants from the wild are available for prices between the above costs. Commercial plants should be shipped by express package service or hand delivered by the supplier and consequently may cost several cents per plant for delivery. The extra cost is well worthwhile because a delay of one to two days can result in substantial or complete plant mortality.

The primary advantage of commercially supplied plants is quantity availability and site delivery in a suitable planting condition. This reduces logistical problems in procuring plants, but the buyer of large quantities should arrange to have material supplied in several smaller shipments coordinated with planting activities. Reducing storage time at the planting site will reduce plant mortality.

Commercial suppliers carry only a limited number of species, and there is a natural tendency to plan wetland plantings around that supply. Nursery-supplied plants are also genetically and physiologically adapted to their growing site and may be difficult to establish and maintain at locations with different edaphic and climatic characteristics. When selecting a nursery, avoid large latitudinal distances between plant source and destination; longitudinal variation is more acceptable. Finally, plants that have been packaged, shipped, and stored before planting may be stressed at time of planting.

Plants collected from the wild are more closely adapted to local environmental conditions than nursery-acquired plants. They can also be planted with limited storage; if collecting and planting are coordinated, they can normally be planted within 36 hours or less after collection. If a diverse natural ecosystem is desirable, natural populations can supply that diversity. Plants for acid mine drainage systems are often obtained from similar habitats because plants from normal habitats occasionally die or need a lengthy acclimatization period. Disadvantages of local collections are (1) undesirable weedy species may be inadvertently included or rare or endangered species populations may be decimated; (2) logistics or difficult collecting conditions may increase costs; (3) plants may not be available because of limited supply, local regulations, or difficult access to private land; and (4) plants may be unavailable early or late in the growing season. Care must be taken to avoid sites that contain noxious weeds or rare, threatened, or endangered species and to distribute collections to avoid permanent damage to the source wetland.

Plants can be grown specifically for a particular project, but this often requires a year or more of lead time, and facilities such as a greenhouse or outdoor nursery must be available. The authors have used nursery beds with soil or fertilized sand to propagate plants. Wild collected or purchased plants are placed in well-watered beds and the plants spread by vegetative growth. In cool temperate climates, a greenhouse should be used only as an oversized cold frame. This permits plants to begin growth a few weeks earlier in the season and allows hydrophyte planting when they are normally dormant and difficult to locate in the wild. The U.S. Army Engineer Waterways Experiment Station has experienced no difficulty in growing smooth cordgrass and willow *(Salix* spp.) in the warm temperate climate of Mississippi. However, in a northern climate, Southern Tier Consulting (New York) has had poor success in breaking dormancy during midwinter, and Environmental Concern (Maryland) has had similar experience.[16]

PLANTING METHODS

Establishing vegetation once a site has been prepared involves planting with a suitable propagule at the appropriate time. The planting period for herbaceous vegetation is broader than for woody plants. In temperate climates, the planting period typically begins after dormancy has begun in the fall and ends after the first third of the summer growing season has passed. Fall dormant planting is recommended for tubers and rootstock and is very successful for some species.[4] Species from the genera of burreed *(Sparganium),* dock *(Rumex),* bulrush *(Scirpus),* rush *(Juncus),* and arrowhead *(Sagittaria)* have been successfully planted in fall, whereas some manna grasses *(Glyceria* spp.), sedges *(Carex* spp.), and cattail *(Typha* spp.) have grown more successfully when transplanted after dormancy has been broken in spring. In general, early spring growing season plantings have been most successful.

Wetlands are generally planted with whole plants or dormant rhizomes and tubers. Establishment from seed typically has not been successful because of stratification requirements of wetland seed and loss of seed via water action. An exception may be when wetland turf or agricultural grasses are used (1) on upper portions of basins that are never flooded or are not flooded until after seeds are established or (2) on saturated drawdown zones of reservoirs shortly after the water has been withdrawn.[5] Also, wet prairie species have been established in the tall grass prairie province by planting wild collected seeds with a seed drill.

Dormant underground vegetative propagules are commonly planted. Tubers of duck potato *(Sagittaria latifolia),* sago pondweed *(Potamogeton pectinatus),* and softstem bulrush *(Scirpus validus)* are commonly and successfully planted. Tubers are simply placed deep enough in the substrate to prevent them from floating out of the medium.[4] Some investigators have had the best success with tubers having 20–25 cm of stem so the plants can obtain enough oxygen through the stem when flooded.

Whole plants with shoots, roots, and active buds also are frequently planted. Some species, such as water smartweeds *(Polygonum coccineum* and *P. hydropiperoides)*, planted in this manner begin to grow immediately from existing buds and root primordia on the shoots. Others, such as most grasses, begin new growth from buds at the plant base, and the existing root and shoot systems die shortly after transplanting. Loss of the shoot does not appear to inhibit establishment and early development of the plants. Use of potted plants avoids this initial phase of death and regrowth.

Cores (8- to 10-cm diameter) of wetland soil and associated propagules collected in existing marshes can be transplanted to constructed wetlands. Van Wormer uses this method because cores are sources of various seed, shoots, and roots of wetland plants that promote development of diverse marshes. The cores also produce plants that avoid the initial dieback of some species. Cores have the disadvantage of the time and cost associated with collecting, transporting intact, and planting the heavy soil mass.

We recommend allowing plantings to become well established before wastewater is introduced into the system; the plants need an opportunity to overcome planting stress before other stresses are introduced. Satisfactory establishment may take one or two full growing seasons. Gradual increase in the concentration of waste applied may also be necessary. Once the system is fully functional, vegetation should be monitored frequently; if dead or unhealthy patches of vegetation are found, they should be replanted and/or the concentrations of wastewater reduced. Simply obtain replacement plantings from the existing treatment system once it is well established.

For planting bare root plants and tubers, a tree planting bar or tile spade is a good tool. A slit is made in the substrate, the propagule is inserted, and the slit is sealed. Plant deep enough to prevent propagules from floating out of the planting hole. If a small hole is required for a wetland core or potted plant, a power auger may be needed on dry soil, or a shovel can be used if planting under water or on wet soil.

Occasionally, special anchoring methods are required when the substrate is soft, plants are buoyant, or erosion will disturb the constructed system. Those methods typically require temporary anchoring using light construction materials. Allen and Klimas[5] provide a good introduction to those techniques. Some wetland plant suppliers suggest weighted propagules can be dropped into calm water as an inexpensive means of planting, but it has been Pierce's experience this method does not provide a large proportion of successful plantings. Additional mechanical protection may be required to prevent animals from damaging newly established plants. Garbisch,[17] Environmental Laboratory,[2] Comes and McCreary,[18] and Pierce and Amerson[7] have suggested methods of preventing animal depredation. Such methods include (1) planting through chicken wire fence fastened to the surface of the substrate to prevent tuber or rhizome excavation and (2) use of unpalatable species.

WATER LEVEL MANAGEMENT

In constructed wetlands, controlling water levels will influence plant survival and desired species composition. Water level is the most critical aspect of plant survival during the first year after planting. A common mistake is to assume that because the plant is a wetland plant, it can tolerate deep water. Frequently, too much water creates more problems for wetland plants during the first growing season than too little water because the plants do not receive adequate oxygen at their roots. Wetland emergent species should be planted in a wet substrate (but not flooded) and allowed to grow enough to generate a stem with leaves that protrude above the initial flooding height. For best survival and growth during the first growing season, the substrate for small stalks (2–5 cm) should only be saturated, not flooded, and as the plants grow the water level can be raised proportionally.

For wet meadow species that grow in the shallow-to-transitional zones (Figure 1), watering during the first year should be limited to shallow sheetflow with intermittent drying periods, depending on the species. Wet meadow species such as spikerushes *(Eleocharis* spp.), fescues *(Festuca* spp.), bluegrasses *(Poa* spp.), bentgrasses *(Agrostis* spp.), and perennial foxtails *(Alopecurus* spp.) will tolerate reasonably long dry periods. Other species, such as manna grasses *(Glyceria* spp.), are not as tolerant and should not become completely dry the first growing season.

Water levels for submergent and floating leaved aquatic plants should never be lowered to the extent that the plants become exposed. The most important criterion for submergents is maintaining water level stability and keeping the plant continuously submerged the first growing season.

Water levels can be manipulated to control prolific growth and spread of weedy plants. For example, cattail may be controlled by deep flooding for several weeks during the growing season after the stems have been cut. Flooding may also inhibit establishment of undesirable opportunistic species.

SUMMARY

Wetland construction involves vegetation techniques related to species choice and plant handling. Choosing species requires knowledge of the hydrologic regime and substrate of the proposed wetland as well as the ecological characteristics of species proposed for planting. The species planted should also have attributes optimizing their desired function in the waste treatment system (e.g., efficient oxygen transmission to roots). Plants acquired from nurseries or collected in the wild must be carefully handled and planted to

promote survival. Once planted, aftercare and water level manipulation will assure a well vegetated and healthy wetland.

ACKNOWLEDGMENTS

Permission was granted by the Chief of Engineers to publish this information. Thanks is extended to Dr. Charles J. Klimas and Mr. Ellis J. Clairain of the U.S. Army Engineer Waterways Experiment Station and to Dr. H. Glenn Hughes of the DuBois Campus, Pennsylvania State University, for their review of the chapter. Reference to companies and specific products in this chapter does not imply endorsement by the authors or any of their employers, such as the U.S. Army Corps of Engineers.

REFERENCES

1. Smith, H. K. "An Introduction to Habitat Development on Dredged Material," Technical Report DS-78-19, U.S. Army Engineer Waterways Experiment Station.
2. "Wetland Habitat Development with Dredged Material: Engineering and Plant Propagation," Technical Report DS-78-16, U.S. Army Engineer Waterways Experiment Station (1978).
3. Knutson, P. L., and W. W. Woodhouse, Jr. "Shore Stabilization with Salt Marsh Vegetation," Special Report No. 9, U.S. Army Corps of Engineers, Coastal Engineering Research Center (1983).
4. Kadlec, J. A., and W. A. Wentz. "State-of-the-Art Survey and Evaluation of Marsh Plant Establishment Techniques: Induced and Natural, Vol. I: Report of Research," Technical Report DS-74-9, U.S. Army Engineer Waterways Experiment Station (1974).
5. Allen, H. H., and C. V. Klimas. "Reservoir Shoreline Revegetation Guidelines," Technical Report E-86-13, U.S. Army Engineer Waterways Experiment Station (1986).
6. Brodie, G. A., D. A. Hammer, and D. A. Tomljanovich. "Constructed Wetlands for Acid Drainage Control in the Tennessee Valley," in *Mine Drainage and Surface Mine Reclamation, Vol. I, Mine Water and Mine Waste,* Bureau of Mines Information Circular 9183 (1988), pp. 325–331.
7. Pierce, G. J., and A. B. Amerson, Jr. "A Pilot Project for Wetlands Construction on the Floodplain of the Allegheny River in Cattaraugus County, New York," in *Proceedings of the Eighth Annual Conference on Wetland Restoration and Creation*, (Tampa, FL: Hillsborough Community College, 1982), pp. 140–153.
8. DuLaunie, R. D., W. H. Patrick, Jr., and J. M. Brannon. "Nutrient Transformations in Louisiana Salt Marsh Soils," Sea Grant Publication No. LSV-T-76-009, Center for Wetland Resources, Louisiana State University (1976).
9. Southern Tier Consulting, and Ecology and Environment, Inc. "Wetland Demonstration Project," Contract No. D250336-CPIN 5119.01.321 STE, Section 5P (A) for Department of Transportation, State of New York (1987).
10. Emerson, F. B., Jr., "Experimental Establishment of Food and Cover Plants in Marshes Created for Wildlife in New York State," *New York Fish Game J.* 8(2):130–144 (1961).

11. Wein, G. R., S. Kroeger, and G. J. Pierce. "Lacustrine Vegetation Establishment Within a Cooling Reservoir," The 14th Annual Conference on Wetland Restoration and Creation, Tampa, FL (1987).
12. Whitlow, T. H., and R. W. Harris. "Flood Tolerance in Plants: A State-of-the-Art Review," Technical Report E-79-2, U.S. Army Engineer Waterways Experiment Station (1979).
13. Stark, L. R., R. L. Kolbash, H. J. Webster, S. E. Stevens, Jr., K. A. Dionis, and E. R. Murphy. "The SIMCO #4 Wetland: Biological Patterns and Performance of a Wetland Receiving Mine Drainage," in *Mine Drainage and Surface Mine Reclamation, Vol. I, Mine Water and Mine Waste,* Bureau of Mines Information Circular 9183 (1988), pp. 332–344.
14. Michaud, S. C., and C. J. Richardson. "Relative Radial Oxygen Loss in Five Wetland Plants," Chapter 38a, this volume.
15. Mitsch, W. J., and J. G. Gosselink. *Wetlands* (New York: Van Nostrand Reinhold Company, 1986).
16. Garbisch, E. W., owner, Environmental Concern Inc., St. Michaels, MD. Personal communication (December 1986).
17. Garbisch, E. W. "Highways and Wetlands: Compensating Wetland Losses," Federal Highway Administration Report No. FHWA-IP-86-22, Turner-Fairbanks Highway Research Center, U.S. Department of Transportation (1986).
18. Comes, R. D., and T. McCreary. "Approaches to Revegetate Shorelines at Lake Wallula on the Columbia River, Washington-Oregon," Technical Report E-86-2, U.S. Army Engineer Waterways Experiment Station (1986).