A HANDBOOK OF CONSTRUCTED WETLANDS

a guide to creating wetlands for:

AGRICULTURAL WASTEWATER
DOMESTIC WASTEWATER
COAL MINE DRAINAGE
STORMWATER

in the Mid-Atlantic Region

Volume 1

GENERAL CONSIDERATIONS

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The findings. conclusions, and recommendations contained in the Handbook do not necessarily represent the policy of the USDA - NRCS, EPA - Region III, the Commonwealth of Pennsylvania, or any other state in the northeastern United States concerning the use of constructed wetlands for the treatment and control of nonpoint sources of pollutants. Each state agency should be consulted to determine specific programs and restrictions in this regard.

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CHAPTER 1
INTRODUCTION

Natural processes have always cleansed water as it flowed through rivers, lakes, streams, and wetlands. In the last several decades, systems have been constructed to use some of these processes for water quality improvement. Constructed wetlands are now used to improve the quality of point and nonpoint sources of water pollution, including stormwater runoff, domestic wastewater, agricultural wastewater, and coal mine drainage. Constructed wetlands are also being used to treat petroleum refinery wastes, compost and landfill leachates, fish pond discharges, and pretreated industrial wastewaters, such as those from pulp and paper mills, textile mills, and seafood processing. For some wastewaters, constructed wetlands are the sole treatment; for others, they are one component in a sequence of treatment processes.

One of the most common applications of constructed wetlands has been the treatment of primary or secondary domestic sewage effluent. Constructed wetland systems modelled after those for domestic wastewater are being used to treat the high organic loads associated with agriculture. A large number of wetlands have been constructed to treat drainage from active and abandoned coal mines and more than 500 such systems are operating in Appalachia alone. The use of constructed wetlands to control stormwater flows and quality is a recent application of the technology and the number of such systems is increasing rapidly.

The treatment of wastewater or stormwater by constructed wetlands can be a low-cost, low-energy process requiring minimal operational attention. As a result of both extensive research and practical application, insight is being gained into the design, performance, operation, and maintenance of constructed wetlands for water quality improvement. Constructed wetlands can be sturdy, effective systems. However, to be effective, they must be carefully designed, constructed, operated, and maintained.

This Handbook has been prepared as a general guide to the design, construction, operation, and maintenance of constructed wetlands for the treatment of domestic wastewater, agricultural wastewater, coal mine drainage, and stormwater runoff in the mid-Atlantic region, The Handbook is not a design manual. The use of constructed wetlands to improve water quality is a developing technology. Much is not yet understood, and questions remain regarding the optimal design of wetland systems and their longevity. As our experience with these systems increases, the information offered here will be replaced by more refined information. The Handbook should be used with this clearly in mind.

The Handbook is divided into five volumes. This, the first, provides information common to all types of constructed wetlands for wastewater and runoff. It is to be used in conjunction with an accompanying volume that provides information specific to a particular type of wastewater or runoff. The other volumes in the series are Volume 2: Domestic Wastewater, Volume 3: Agricultural Wastewater, Volume 4: Coal Mine Drainage, and Volume 5: Stormwater Runoff. While constructed wetlands are being used to treat other kinds of wastewater, such as industrial wastewaters, a discussion of these applications is beyond the scope of this Handbook. However, the information presented here may be useful in developing other applications.

A number of conferences on constructed wetlands have been held recently. The proceedings of these conferences include experimental and operational data from wetland systems built to treat a number of different kinds of wastewaters and runoff, and present detailed discussions of process kinetics and system design. Proceedings from three well-known conferences are:

Moshiri, G. A. (ed.) 1993. *Constructed Wetlands for Water Quality Improvement.* CRC Press, Boca Raton, FL. 632 pp.

Cooper, P. F., and B. C. Findlater (eds.) 1990. ***Constructed Wetlands in Water Pollution Control.*** Proceedings of the International Conference on the Use of Constructed Wetlands in Water Pollution Control. Cambridge, UK, 24-28 September. WRc, Swindon, Wiltshire, UK. 605 pp.

Hammer, D. A. (ed.) 1989. *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and* Agricultural. Lewis Publishers. Chelsea, MI. 831 pp.

Conferences and published' information continue to become available as more constructed wetland systems are built and monitored.

CHAPTER 2
CONSTRUCTED WETLANDS AS ECOSYSTEMS

Constructed wetlands for water treatment are complex, integrated systems of water, plants, animals, microorganisms, and the environment. While wetlands are generally reliable, self-adjusting systems, an understanding of how natural wetlands are structured and how they function greatly increases the likelihood of successfully constructing a treatment wetland. This chapter provides an overview of the major components of wetland ecosystems and of the most important processes that affect water treatment.

WHAT ARE WETLANDS?

Wetlands are transitional areas between land and water. The boundaries between wetlands and uplands or deep water are therefore not always distinct. The term "wetlands" encompasses a broad range of wet environments, including marshes, bogs, swamps, wet meadows, tidal wetlands, floodplains, and ribbon (riparian) wetlands along stream channels.

All wetlands - natural or constructed, freshwater or salt - have one characteristic in common: the presence of surface or near-surface water, at least periodically. In most wetlands, hydrologic conditions are such that the substrate is saturated long enough during the growing season to create oxygen-poor conditions in the substrate. The lack of oxygen creates reducing. (oxygen-poor) conditions within the substrate and limits the vegetation to those species that are adapted to low-oxygen environments.

The hydrology of wetlands is generally one of slow flows and either shallow waters or saturated substrates. The slow flows and shallow water depths allow sediments to settle as the water passes through the wetland. The slow flows also provide prolonged contact times between the water and the surfaces within the wetland. The complex mass of organic and inorganic materials and the diverse opportunities for gas/water interchanges foster a diverse community of microorganisms that break down or transform a wide variety of substances.

Most wetlands support a dense growth of vascular plants adapted to saturated conditions. This vegetation slows the water, creates microenvironments within the water column, and provides attachment sites for the microbial community. The litter that accumulates as plants die back in the fall creates additional material and exchange sites, and provides a source of carbon, nitrogen, and phosphorous to fuel microbial processes.

WETLAND FUNCTIONS AND VALUES

Wetlands provide a number of functions and values. (Wetland functions are the inherent processes occurring in wetlands; wetland values are the attributes of wetlands that society perceives as beneficial.) While not all wetlands provide all functions and values, most wetlands provide several. Under appropriate circumstances. constructed wetlands can provide:

- water quality improvement
- flood storage and the desynchronization of storm rainfall and surface runoff
- cycling of nutrients and other materials
- habitat for fish- and wildlife
- passive recreation, such as bird watching and photography
- active recreation, such as hunting
- education and research
- aesthetics and landscape enhancemerit.'

COMPONENTS OF CONSTRUCTED WETLANDS

A constructed wetland consists of a properly-designed basin that contains water, a substrate, and, most commonly, vascular plants. These components can be manipulated in constructing a wetland. Other important components of wetlands, such as the communities of microbes and aquatic invertebrates, develop naturally.

WATER

Wetlands are likely to form where landforms direct surface water to shallow basins and where a relatively impermeable subsurface layer prevents the surface water from seeping into the ground. These conditions can be created to construct a wetland. A wetland can be built almost anywhere in the landscape by shaping the land surface to collect surface water and by sealing the basin to retain the water.

Hydrology is the most important design factor in constructed wetlands because it links all of the functions in a wetland and because it is often the primary factor in the success or failure of a constructed wetland. While the hydrology of constructed wetlands is not greatly different than that of other surface and near-surface waters, it does differ in several important respects:

- small changes in hydrology can have fairly significant effects on a wetland and its treatment effectiveness
- because of the large surface area of the water and its shallow depth, a wetland system interacts strongly with the atmosphere through rainfall and evapotranspiration (the combined loss of water by evaporation from the water surface and loss through transpiration by plants)
- the density of vegetation of a wetland strongly affects its hydrology, first, by obstructing flow paths as the water finds its sinuous way through the network of stems, leaves, roots, and rhizomes and, second, by blocking exposure to wind and sun.

SUBSTRATES, SEDIMENTS, AND LITTER

Substrates used to construct wetlands include soil, sand, gravel, rock, and organic materials such as compost. Sediments and litter then accumulate in the wetland because of the low water velocities and high productivity typical of wetlands. The substrates, sediments, and litter are important for several reasons:

- they support many of the living organisms in wetlands
- substrate permeability affects the movement of water through the wetland
- many chemical and biological (especially microbial) transformations take place within the substrates
- substrates provide storage for many contaminants
- the accumulation of litter increases the amount of organic matter in the wetland. Organic matter provides sites for material exchange and microbial attachment, and is a source of carbon, the energy source that drives some of the important biological reactions in wetlands.

The physical and chemical characteristics of soils and other substrates are altered when they are flooded. In a saturated substrate, water replaces the atmospheric gases in the pore spaces and microbial metabolism consumes the available oxygen. Since oxygen is consumed more rapidly than it. can be replaced by diffusion from the atmosphere, substrates become anoxic (without oxygen). This reducing environment is important in the removal of pollutants such as nitrogen and metals.

VEGETATION

Both vascular plants (the higher plants) and non-vascular plants (algae) are important in constructed wetlands. Photosynthesis by algae increases the dissolved oxygen content of the water which in turn affects nutrient and metal

Constructed wetlands attract waterfowl and wading birds, including mallards, green-winged teal, wood ducks, moorhens, green and great blue herons, and bitterns. Snipe, red-winged blackbirds, marsh wrens, bank swallows, red-tailed hawks, and Northern harriers feed and/or nest in wetlands.

Aesthetics and Landscape Enhancement

While wetlands are primarily treatment systems, they provide intangible benefits by increasing the aesthetics of the site and enhancing the landscape. Visually, wetlands are unusually rich environments. By introducing the element of water to the landscape, constructed wetlands, as much as natural wetlands. add diversity to the landscape. The complexity of shape, color, size, and interspersion of plants, and the variety in the sweep and curve of the edges of landforms all add to the aesthetic quality of the wetlands. Constructed wetlands can be built with curving shapes that follow the natural contours of the site, and some wetlands for water treatment are' indistinguishable, at first glance, from natural wetlands.

reactions. Vascular plants contribute to the treatment of wastewater and runoff in a number of ways:

- they stabilize substrates and limit channelized flow
- they slow water velocities, allowing suspended materials to settle
- they take up carbon, nutrients, and trace elements and incorporate them into plant tissues
- they transfer gases between the atmosphere and the sediments
- leakage of oxygen from subsurface plant structures creates oxygenated microsites within the substrate
- their stem and root systems provide sites for microbial attachment
- theycreate litter when they die and decay.

Constructed wetlands are usually planted with emergent vegetation (non-woody plants that grow with their roots in the substrate and their stems and leaves emerging from the water surface). Common emergents used in constructed wetlands include bulrushes, cattails, reeds, and a number of broad-leaved species.

MICROORGANISMS

A fundamental characteristic of wetlands is that their functions are largely regulated by microorganisms and their metabolism (Wetzel 1993). Microorganisms include bacteria, yeasts, fungi, protozoa, rind algae. The microbial biomass is a major sink for organic carbon and many nutrients. Microbial activity:

- transforms a great number of organic and inorganic substances into innocuous or insoluble substances
- alters the reduction/oxidation (redox) conditions of the substrate and thus affects the processing capacity of the wetland
- is involved in the recycling of nutrients.

Some microbial transformations are aerobic (that is, they require free oxygen) while others are anaerobic (they take place in the absence of free oxygen). Many bacterial species are facultative anaerobes, that is, they are capable of functioning under both aerobic and anaerobic conditions in response to changing environmental conditions.

Microbial populations adjust to changes in the water delivered to them. Populations of microbes can expand quickly when presented with suitable energy-containing materials. When environmental conditions are no longer suitable, many microorganisms become dormant and can remain dormant for years (Hilton 1993).

The microbial community of a constructed wetland can be affected by toxic substances, such as pesticides and heavy metals, and care must be taken to prevent such chemicals from being introduced at damaging concentrations.

ANIMALS

Constructed wetlands provide habitat for a rich diversity of invertebrates and vertebrates. Invertebrate animals, such as insects and worms. contribute to the treatment process by fragmenting detritus and consuming organic matter. The larvae of many insects are aquatic and consume significant amounts of material during their larval stages, which may last for several years. Invertebrates also fill a number of ecological roles; for instance, dragonfly nymphs are important predators of mosquito larvae.

Although invertebrates are the most important animals as far as water quality improvement is concerned, constructed wetlands also attract a variety of amphibians, turtles, birds, and mammals.

CHAPTER 3
CONSTRUCTED WETLANDS AS TREATMENT SYSTEMS

A constructed wetland is a shallow basin filled with some sort of substrate, usually soil or gravel, and planted with vegetation tolerant of saturated conditions. Water is introduced at one end and flows over the surface or through the substrate, and is discharged at the other end through a weir or other structure which controls the depth of the water in the wetland.

HOW WETLANDS IMPROVE WATER QUALITY

A wetland is a complex assemblage of water, substrate, plants (vascular and algae), litter (primarily fallen plant material), invertebrates (mostly insect larvae and worms). and an array of microorganisms (most importantly bacteria). The mechanisms that are available to improve water quality are therefore numerous and often interrelated. These mechanisms include:

- settling of suspended particulate matter
- filtration and chemical precipitation through contact of the water with the substrate and litter
- chemical transformation
- adsorption and ion exchange on the surfaces of plants, substrate, sediment, and litter
- breakdown and transformation of pollutants by microorganisms and plants
- uptake and transformation of nutrients by microorganisms and plants
- predation and natural die-off of pathogens.

The most effective treatment wetlands are those that foster these mechanisms. The specifics for the various types of wastewater and runoff are discussed in the wastewater-specific volumes.

ADVANTAGES OF CONSTRUCTED WETLANDS

Constructed wetlands are a cost-effective and technically feasible approach to treating wastewater and runoff for several reasons:

- wetlands can be less expensive to build than other treatment options
- operation and maintenance expenses (energy and supplies) are low
- operation and maintenance require only periodic, rather than continuous, on-site labor
- wetlands are able to tolerate fluctuations in **flow**
- they facilitate water reuse and recycling.

In addition:

- they provide habitat for many wetland organisms
- they can be built to fit harmoniously into the landscape
- they provide numerous benefits in addition to water quality improvement, such as wildlife habitat and the aesthetic enhancement of open spaces
- they are an environmentally-sensitive approach that is viewed with favor by the general public.

LIMITATIONS OF CONSTRUCTED WETLANDS

There are limitations associated with the use of constructed wetlands:

- they generally require larger land areas than do conventional wastewater treatment systerns. Wetland treatment may be economical relative to other options only where land is available and affordable.

- performance may be less consistent than in conventional treatment. Wetland treatment efficiencies may vary ‘seasonally in response to changing environmental conditions, including rainfall and drought. While the average performance over the year may be acceptable, wetland treatment cannot be relied upon if effluent quality must meet stringent discharge standards at all times.
- the biological components are sensitive to toxic chemicals, such as ammonia and pesticides
- flushes of pollutants or surges in water flow may temporarily reduce treatment effectiveness
- they require a minimum amount of water if they are to survive. While wetlands can tolerate temporary drawdowns, they cannot withstand complete drying.

Also, the use of constructed wetlands for wastewater treatment and stormwater control is a fairly recent development. There is yet no consensus on the optimal design of wetland systems nor is there much information on their long-term performance.

TYPES OF CONSTRUCTED WETLANDS

There are several types of constructed wetlands: surface flow wetlands, subsurface flow wetlands, and hybrid systems that incorporate surface and subsurface flow wetlands. Constructed wetland systems can also be combined with conventional treatment technologies. The types of constructed wetlands appropriate for domestic wastewater, agricultural wastewater, coal mine drainage, and stormwater runoff are discussed in the wastewater-specific volumes.

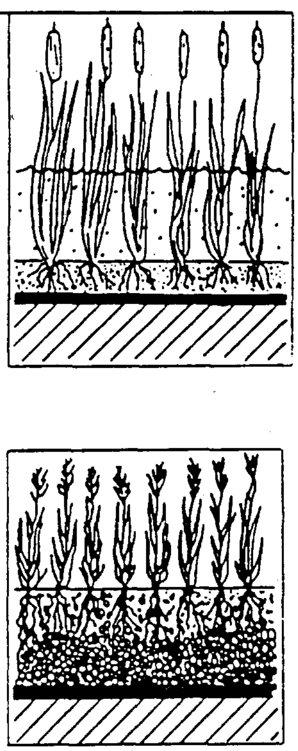

Figure 1. Surface flow and subsurface flow constructed wetlands (from Water Pollution Control Federation 1990).

Surface Flow Wetlands

A surface flow (SF) wetland consists of a shallow basin, soil or other medium to support the roots of vegetation, and a water control structure that maintains a shallow depth of water (figure 1). The water surface is above the substrate. SF wetlands look much like natural marshes and can provide wildlife habitat and aesthetic benefits as well as water treatment. In SF wetlands, the near-surface layer is aerobic while the deeper waters and substrate are usually anaerobic. Stormwater wetlands and wetlands built to treat mine drainage and agricultural runoff are usually SF wetlands.

SF wetlands are sometimes called free water surface wetlands or, if they are for mine drainage, aerobic wetlands. The advantages of SF wetlands are that their capital and operating costs are low, and that their construction, operation, and maintenance are straightforward. The main disadvantage of SF systems is that they generally require a larger land area than other systems.

Subsurface Flow Wetlands

A subsurface flow (SSF) wetland consists of a sealed basin with a porous substrate of rock or gravel. The water level is designed to remain below the top of the substrate. In most of the systems in the United States, the flow path is horizontal, although some European systems use vertical flow paths. SSF systems are called by several names. including vegetated submerged bed, root zone method, microbial rock reed filter, and plant-rock filter systems.

Because of the hydraulic constraints imposed by the substrate, SSF wetlands are best suited to wastewaters with relatively low solids concentrations and under relatively uniform flow conditions. SSF wetlands have most frequently been used to reduce 5-day biochemical oxygen demand (BOD_5) from domestic wastewaters.

The advantages cited for SSF wetlands are greater cold tolerance, minimization of pest and odor problems, and, possibly, greater assimilation potential per unit of land area than in SF systems. It has been claimed that the porous medium provides greater surface area for treatment contact than is found in SF wetlands, so that the treatment responses should be faster for SSF wetlands which can, therefore, be smaller than a SF system designed for the same volume of wastewater. Since the water surface is not exposed, public access problems are minimal. Several SSF systems are operating in parks. with public access encouraged.

The disadvantages of SSF wetlands are that they are more expensive to construct, on a unit basis. than SF wetlands. Because of cost, SSF wetlands are often used for small flows. SSF wetlands may be more difficult to regulate than SF wetlands, and maintenance and repair costs are generally higher than for SF wetlands. A number of systems have had problems with clogging and unintended surface flows.

Hybrid Systems

Single stage systems require that all of the removal processes occur in the same space. In hybrid or multistage systems, different cells are designed for different types of reactions. Effective wetland treatment of mine drainage may require a sequence of different wetland cells to promote aerobic and anaerobic reactions. as may the removal of ammonia from agricultural wastewater.

WINTER AND SUMMER OPERATION

Wetlands continue to function during cold weather. Physical processes, such as sedimentation. continue regardless of temperature, providing that the water does not freeze. Many of the reactions take place within the wetland substrate, where decomposition and microbial activity generate enough heat to keep the subsurface layers from freezing. Water treatment will continue under ice. To create space for under-ice flow, water levels can be raised in anticipation of freeze, then dropped once a cover of ice has formed.

Rates of microbial decomposition slow as temperatures drop and the wetland may need to be made larger to accommodate the slower reaction rates. For agricultural wetlands, which rely on microbial activity to break down organic wastes, it may be prudent to store the wastewater in the pretreatment unit during the cold months for treatment during the warm months. The high flows that are common in winter and spring because of snowmelt, spring rains, and high groundwater tables can move water so quickly through a wetland that there is not enough retention time for adequate treatment. Because removal rates are much higher during warm weather, the agricultural wetland can often be smaller than if the water were treated year-round.

Wetlands lose large amounts of water in the summer through evapotranspiration. The adequacy of flow in the summer must be considered since it will affect water levels in the wetland and the amount of wetland effluent available for recycling (if this is part of the design). A supplemental source of water may be required to maintain adequate moisture in the wetland.

CREATION OF HAZARD

The question of hazard arises from the fact that, in ecological terms, everything must go somewhere. Wetlands are able to degrade, transform, or assimilate many contaminants, such nitrogen, and are sinks for some materials. For persistent materials, such as phosphorous and metals, wetland sinks may become sources if not properly constructed and managed. The extent to which wetlands retain contaminants such as phosphorous and metals is an important unknown factor, as are the conditions under which wetlands may release stored contaminants. Bioaccumulation and biotoxicity in treatment wetlands is not clearly documented nor understood.

Persistent compounds can be a concern, depending on the constituents in the wastewater. For instance, mine drainage contains metals and stormwater carries hydrocarbons deposited on paved surfaces. Heavy metals are often sequestered in wetland sediments that may be washed out of wetlands during storms, thereby providing only a lag time in pollutant dispersal. Transport of toxic materials in this way is a concern, as is the transport of phosphorus, an extremely important factor in the over-enrichment of surface waters. The question of hazard underscores the importance of designing and operating constructed wetlands properly and monitoring them periodically.

CHANGE AND RESILIENCE

All ecosystems change over time. Wetlands for wastewater treatment can be expected to change more quickly than most natural wetlands because of the rapid accumulation of sediment, litter, and pollutants. Some natural variability is also inherent in all living systems and is to be expected.

The change in species composition as ecosystems mature is known as succession. In general, species diversity increases as ecosystems mature. Diversity (the number of species within a habitat, such as a wetland) is often considered a measure of ecosystem resilience (the ability of the system to accept disturbance): as the number of species increases, so does the complexity of the interactions of the different species with each other and with their environment; the greater the number of interactions, the more resilient the system is as a whole and the broader its capacity to adapt to change.

In wastewater treatment wetlands, the stresses of high wastewater loadings can lead to dominance by a few aggressive, highly tolerant species, such as cattail and common reed, which may eventually eliminate other species. If wildlife habitat values are important to the project, intervention to maintain diversity may be necessary. If habitat values are not important, changes can be allowed to proceed without interference as long as the wetland continues to treat the water to acceptable levels.

Any ecosystem, natural or constructed, has limits to its ability to accept disturbance. The performance of constructed wetland systems may change over time as a consequence of changes in the substrate and the accumulation of pollutants in the wetland. Constructed wetlands must be monitored periodically for evidence of stress so that remedial action, if necessary, can be taken.

CHAPTER 4
GENERAL DESIGN OF CONSTRUCTED WETLANDS

DESIGN CONSIDERATIONS

Despite a large amount of research and published information, the optimal design of constructed wetlands for various applications has not yet been determined. Many constructed wetland systems have not been adequately monitored or have not been operating long enough to provide sufficient data for analysis. Among the systems that have been monitored, performance has varied and the influences of the diverse factors that affect performance, such as location, type of wastewater or runoff, wetland design, climate, weather, disturbance, and daily or seasonal variability, 'have been difficult to quantify.

In general, wetland designs attempt to mimic natural wetlands in overall structure while fostering those wetland processes that are thought to contribute the most to the improvement of water quality. Mitsch (1992) suggests the following guidelines for creating successful constructed wetlands:

- keep the design simple. Complex technological approaches often invite failure.
- design for minimal maintenance.
- design the system to use natural energies, such as gravity flow.
- design for the extremes of weather and climate, not the average. Storms, floods, and droughts are to be expected and planned for, not feared.
- design the wetland with the landscape, not against it. Integrate the design with the natural topography of the site.
- avoid over-engineering the design with rectangular basins, rigid structures and channels, and regular morphology. Mimic natural systems.
- give the system time. Wetlands do not necessarily become functional overnight and several years may elapse before performance reaches optimal levels. Strategies that try to short-circuit the process of system development or to over-manage often fail.
- design the system for function, not form. For instance, if initial plantings fail, but the overall function of the wetland, based on initial objectives, is intact, then the system has not failed.

PLANNING

A conceptual planning phase is essential. Wetlands can be designed in a variety of system types and configurations to meet specific wastewater needs, alternative sites are often available, and a variety of local, native plant species can be chosen. Every site is unique and the design of a constructed wetland system will be site-specific.

The planning phase consists of characterizing the quantity and quality of the wastewater to be treated, determining the discharge standards to be met, selecting the site, selecting system type and configuration, and specifying the design criteria to be met by the detailed engineering plans. Economic factors include the land area required. the type of water containment, the control and transport of water through the system, and vegetation. Setting and prioritizing the objectives of the wetland system is key to the creation of a successful system. The characteristics of a local natural wetland should be used as a model for the constructed wetland, modified to fit the needs of the project and the specifics of the constructed wetland site.

A constructed wetland should be designed to take advantage of the natural features of the site and to minimize its disturbance. Wetland shape is dictated by the existing topography, geology, and land availability. The number of cells depends on topography, hydrology, and water quality. On level sites, cells can be created with dikes. On sloping sites, cells can be terraced.

A site-sensitive design that incorporates existing features of the site reduces the amount of earthmoving required and increases the visual attractiveness of the site. Earth grading and shaping can blend newly created landforms into the existing landscape. Basins and channels can be curved to follow the natural contours of the site. Various types of vegetation can be planted in and around a constructed wetland to reduce erosion, screen views, define space, control microclimate, and control traffic patterns.

Planning should be oriented toward the creation of a biologically and hydrologically functional system. Plans should include clear goal statements and standards for success. The possible future expansion of the operation should be considered.

Plans should include detailed instructions for implementing a contingency plan in case the system does not achieve its expected performance within a specified time. Plans should be reviewed and approved by the appropriate regulatory agencies.

SITE SELECTION

Selecting an appropriate location can save significant costs. Site selection should consider land use and access, the availability of the land, site topography, soils, the environmental resources of the site and adjoining 1and, and possible effects on any neighbors. The site should be located as close to the source of the wastewater as possible, and downgradient if at all possible so that water can move through the system by gravity. While a wetland can be fitted to almost any site, construction costs can be prohibitively high if extensive earthmoving or expensive liners are required.

A site that is well suited for a constructed wetland is one that:

- is conveniently located to the source of the wastewater
- provides adequate space
- is gently sloping, so that water can flow through the system by gravity
- contains soils that can be sufficiently compacted to minimize seepage to groundwater
- is above the water table
- is not in a floodplain
- does not contain threatened or endangered species
- does not contain archaeological or historic resources.

LAND USE AND ACCESS

Access is an important consideration, **The wet-**land should be placed so that the water can flow by gravity. If the odors or insects could be a problem, as with some agricultural wastewaters, the wetland should be placed as far from dwellings as possible. The site should be accessible to personnel, delivery vehicles, and equipment for construction and maintenance.

For agricultural and some domestic wastewaters, the wetland may be installed on private land. The landowner must be carefully chosen. It is essential that the landowner is cooperative and fully understands the limitations and uncertainties associated with a developing technology such as constructed wetland treatment.

The current and future use and values of adjoining land also will affect the suitability of a site for a constructed wetland. The opinions of area residents and those of environmental and public interest groups should be considered. A large buffer zone should be placed between the wetland and neighboring property. The wetland should not be placed next to the edge of the property.

LAND AVAILABILITY

The effectiveness of a constructed wetland in treating wastewater or stormwater is related to the retention time of the water in the wetland. The usefulness of a constructed wetland may therefore be limited by the size of the wetland needed for adequate retention time. The site selected should be large enough to accommodate present requirements and any future expansion.

Topography

Landform considerations include shape, size, and orientation to the prevailing winds. While a constructed wetland can be built almost anywhere, selecting a site with gradual slopes that can be easily altered to collect and hold water simplifies design and construction, and minimizes costs.

Previously drained wetland areas, including prior converted (PC) agricultural sites, may be well-suited for a constructed wetland since the topography is usually conducive to gravity flow. The appropriate regulatory agencies must be contacted before disturbing any PC site.

Since the best location for a constructed wetland is a low, flat area where water flows by gravity, it is important to ensure that the area is not already a wetland: not all wetlands have standing water throughout the year. The Natural Resources Conservation Service (NRCS), the US Fish and Wildlife Service, or state regulatory personnel should be contacted to determine whether or not a site contains jurisdictional wetlands.

Environmental Resources

To avoid damaging important resources on the site, the presence or absence of significant environmental resources must be determined. Sources of information that can be helpful in selecting a site include the US Geological Survey Topographic Quadrangle maps, and National Aerial Photography Program (NAPP) and and National High Altitude Photography Program (NHAPP) photographs. Geographical information system (GIS) maps are also available.

The National Wetlands Inventory (NWI) maps and the County Soil Survey with the list of county hydric soils should be checked for possible locations of existing wetlands. However, the NW1 maps are based on aerial photography and may not show small wetlands or the less obvious wetlands (wet meadows, vernal pools, and some forested wetlands) and the NW1 information should be field-checked by a wetlands scientist. Historical aerial photography, such as the Agricultural Stabilization and Conservation Service (ASCS) crop compliance photography and county soil survey information, can be useful in identifying hydric soils and drained wetlands that may be difficult to detect otherwise.

Surface and groundwater considerations include possible flooding and drainage problems, location and depth of aquifers, and the location, extent, and classification of receiving waters such as streams and groundwater. A constructed wetland should not be sited on a floodplain unless special measures can be taken to limit its impact on the floodway. Floodplain elevations can often be determined from sources such as Federal Flood Insurance maps or from the Federal Land Management Agency. Landuser input may be the best source of information for assessing previous hydrologic conditions.

US Fish and Wildlife Service and state natural resource agencies should be contacted regarding the potential for significant habitat, or habitat for rare or endangered species. The possible presence of archaeological resources should be verified.

Permits and Regulations

The appropriate agency(ies) must be contacted to determine the regulatory requirements for a proposed constructed wetland and its discharge. Work in a waterway or natural wetland requires a permit. Discharges to natural waters also require a permit. In some zoned communities, zoning approval may be required.

Any stormwater plan must meet local and state stormwater regulations. Some local ordinances have incorporated stormwater provisions which must be complied with. Stormwater regulations vary from place to place and should be consulted before developing a stormwater management plan. The regulatory status of a proposed stormwater wetland, and its relationship to streams and any nearby natural wetlands, must be discussed with the state and/or federal wetland permitting agency before site plans are decided upon.

STRUCTURES

CELLS

Wetlands can be constructed by excavating basins, by building up earth embankments (dikes), or by a combination of the two.

Dikes must be constructed of soils with adequate fine-grained material that will compact into arelatively stable and impervious embankment. The dikes should be high enough to contain the expected volume plus ample freeboard to accommodate occasional high flows as well as the buildup of litter and sediment over time. To ensure long-term stability. dikes should be sloped no steeper than 2H:lV and riprapped or protected by erosion control fabric on the slopes. An emergency spillway should be provided.

If multiple cells are used, divider dikes can be used to separate cells and to produce the desired length-to-width ratios. On steep sites, they can be used to terrace cells. Dikes can also be used to control flow paths and minimize short-circuiting. Finger dikes are often used to create serpentine flow paths and can be added to operational systems to mitigate short-circuiting. Finger dikes can be constructed of soils, sandbags, straw bales, or treated lumber.

Bottom slopes are generally not critical. An exception may be mine drainage wetlands that use subsurface flow through deep beds of compost to induce sulfate reduction; these cells should slope about 1 - 3% upstream. Bottoms should be relatively level from side to side.

Muskrats can damage dikes by burrowing into them. Although muskrats generally prefer to start their burrows in water than is more than 3 ft deep, they can be a problem in shallower waters. Muskrats can be excluded by installing electric fence low to the ground or by burying muskrat-proof wire mats in the dikes during construction.

LINERS

Constructed wetlands must be sealed to avoid possible contamination of groundwater and also to prevent groundwater from infiltrating into the wetland. Where on-site soils or clay provide an adequate seal, compaction of these materials may be sufficient to line the wetland. Sites underlain by karst, fractured bedrock, or gravelly or sandy soils will have to be sealed by some other method. It may be necessary to have a laboratory analyze the construction material before choosing a sealing method. On-site soils can be used if they can be compacted to permeability of $<10^{8}$ ft/sec ($<10^{-6}$ cm/sec). Soils that contain more than 15% clay are generally suitable. Bentonite, as well as other clays, provide adsorption/reaction sites and contribute alkalinity. The SCS (now the NRCS) South National Technical Center (SNTC) Technical Note 716, “Design and Construction Guidelines for Considering Seepage from Agricultural Waste Storage Ponds and Treatment Lagoons” (1993) and its companion SNTC Technical Note 717, “Measurement and Estimation of Permeability of Soils for Animal Waste Storage Facilities:’ (1991) provide guidance in determining when in-situ soils will adequately meet seepage control needs.

Synthetic liners include asphalt, synthetic butyl rubber, and plastic membranes (for example, 0.5 to 10.0 mil high density polyethylene). The liner must be strong, thick, and smooth to prevent root attachment or penetration. If the site soils contain angular stones, sand bedding or geotextile cushions should be placed under the liner to prevent punctures. The liner should be covered with 3 - 4 inches of soil to prevent the roots of the vegetation from penetrating the liner. If the wetland is to be used for mine drainage, the reaction of the clay or synthetic liner should be tested before it is used since some clays and synthetics are affected by some acid mine drainages.

FLOW CONTROL STRUCTURES

Water levels are controlled by flow control structures. Flow control structures should be simple and easy to adjust. They should allow flexibility so that processes can be optimized initially and adjusted later in response to system changes. 'Multiple inlets must be fully and independently adjustable to ensure an even distribution of flow. Structures should be sized to handle maximum design flows and should be located for easy access and to minimize short-circuiting. Boardwalks and piers make access easy and reduce disturbance of the wetland. PVC pipe is recommended.

If the wetland will be accessible to the public, or located in an isolated area where it will be vulnerable to vandalism, inlet and outlet structures should be enclosed in lockable concrete structures or manholes to avoid damage or tampering with water level settings. Structures must be protected against damage by animals. Measures include installing covers or wire mesh over openings, and enclosing controls, gauges and monitoring devices in pipes or boxes.

Inlets

Inlets at SF wetlands are usually simple: an open-end pipe, channel, or gated pipe which releases water into the wetland (figure 2). The smaller the length-to-width ratio, the more impor-

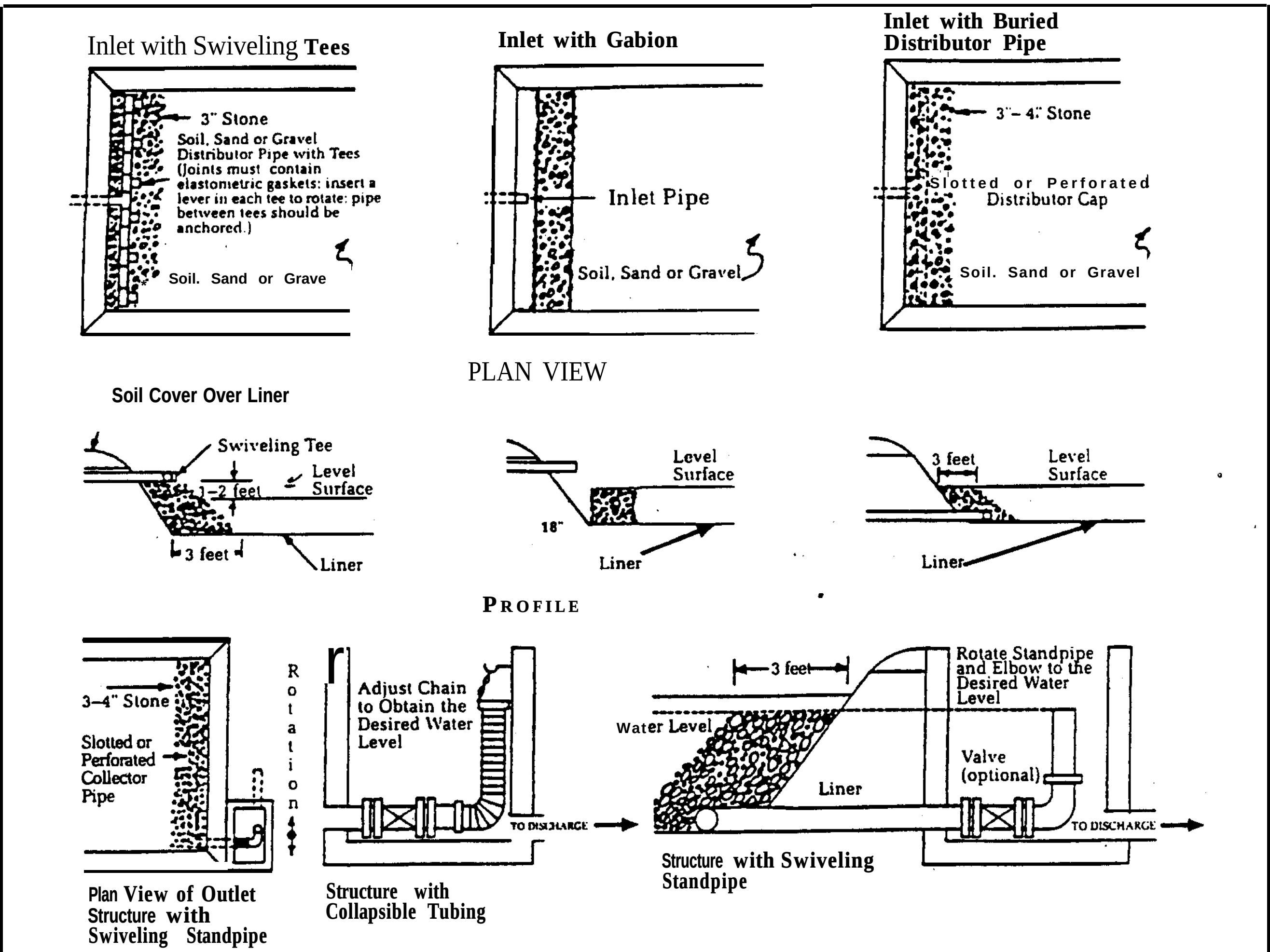

Figure 2. Inlet and outlet designs (modified from Watson and Hobson **1989).**

tant equal flow distribution becomes. Accessible and easily adjustable inlets are mandatory for systems with small length-to-width ratios.

Inlet structures at SSF systems include surface and subsurface manifolds, open trenches perpendicular to the direction of flow, and simple single-point weir boxes. A subsurface manifold avoids the buildup of algal slimes and the consequent clogging that can occur next to surface manifolds, but is difficult to adjust and maintain. A surface manifold, with adjustable outlets provides the maximum flexibility for future adjustments and maintenance, and is recommended. A surface manifold also avoids back-pressure problems. The distance above the water surface of the wetland is typically 12 - 24 inches. The use of coarse rock (3 - 6 inches, 8 - 16 cm) in the entry zone ensures rapid infiltration and prevents ponding and algal growth. To discourage the growth of algae, open water areas near the outlet should be avoided. Shading with either vegetation or a structure in the summer and some thermal protection in the winter will probably be necessary.

A flow splitter will be needed for parallel cells. A typical design consists of a pipe, flume, or weir with parallel orifices of equal size at the same elevation (figure 31. Valves are impractical because they require daily adjustment. Weirs are relatively inexpensive and can be easily replaced or modified. Flumes minimize clogging in applications with high solids but are more expensive than weirs.

Outlets

At SF wetlands, the water level is controlled by the outlet structure, which can be a weir, spillway, or adjustable riser pipe. A variable-

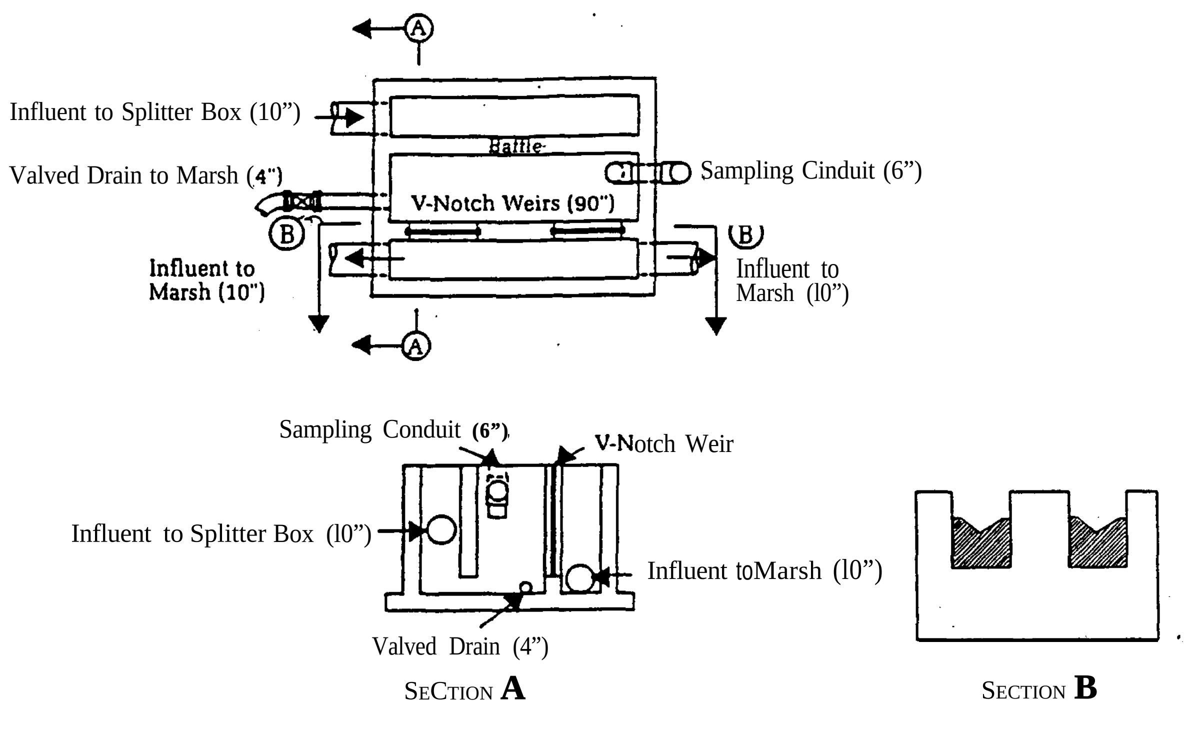

Figure 3. lnfluent splitter box
(modified from Watson and Hobson 1989).

height weir, such as a box with removable stoplogs., allows the water levels to be adjusted easily. Spillways are simple to construct but are not adjustable; incorrect water levels can lead to wetland failure and correcting spillway height can be difficult.

Weirs and spillways must be designed to pass the maximum probable flow. Spillways should consist of wide cuts in the dike with side slopes no steeper than 2H:1V and lined with non-biodegradable erosion control fabric. If high flows are expected, coarse riprap should be used. Vegetated spillways overlying erosion control fabric provide the most natural-looking and stable spillways. Weirs or spillways should be used for mine drainage wetlands since pipes tend to clog with deposits of iron precipitates.

Adjustable riser pipes or flexible hoses offer simple water level control (figure 2). A PVC elbow attached to a swivel offers easy control of the water level. If pipes are used, small diameter (<l2 inch) pipes should be avoided because they clog with litter.

At SSF wetlands, outlets include subsurface manifold, and weir boxes or similar gated structures. The manifold should be located just above the bottom of the bed to provide for complete water level control, including draining. The use of an adjustable outlet, which is recommended to maintain an adequate hydraulic gradient in the bed, can also have significant benefits in operating and maintaining the wetland. The surface of the bed can be flooded to encourage the development of newly planted vegetation and to suppress undesirable weeds, and the water level can be lowered in anticipation of major storms and to provide additional thermal protection against freezing in the winter. The design of SSF beds should allow controlled flooding to 6 inches (15 cm) to foster desirable plant growth and to control weeds. A perforated subsurface manifold connected to an adjustable outlet offers the maximum flexibility and reliability as the outlet device for SSF systems. Since the manifold is buried and inaccessible after construction, careful grading and subbase compaction are required during construction, and clean-out risers in the line must be provided.

The final discharge point from the wetland system should be placed high enough above the receiving water that a rise in the water level in the receiving water, for instance after a storm, will not interfere with the flow of water through the wetland.

SYSTEM LIFETIMES

A constructed wetland used for wastewater treatment may have a finite lifetime which will be determined by wastewater loadings, the capacity of the wetland to remove and store contaminants, and the buildup of litter. A number of systems have been operating for more than 20 years with little, if any, loss of effectiveness. Long-term data on the performance of constructed wetlands are being acquired as more systems are being monitored for longer periods of time. Data from the few constructed wetland systems that have provided long-term data show that treatment performance for pollutants that are broken down in wetlands, such as BOD_5, total suspended solids (TSS), and nitrogen, does not decrease as long as loadings are reasonable, and the wetland system is designed'., built, and maintained with care.

For pollutants that are retained within a wetland, such as phosphorous and metals, the capacity of the wetland to remove and store the pollutants may decrease over time. The buildup of these substances must be monitored periodically to assess the wetland's performance. Wetlands can be sized to accommodate the accumulation of deposits. It is generally assumed that deposition of contaminants in sediments and litter constitutes a relatively long-term sink for contaminants. If necessary, wetland sediments and litter can be removed periodically and the wetland rebuilt with fresh substrate.

CHAPTER 5
HYDROLOGY

The hydrology of a constructed wetland is perhaps the most important factor in its effectiveness. However, the design of constructed wetland treatment systems is still in a state of flux and there remain a number of uncertainties that will not be answered until the results of longer and more numerous operational studies become available. Many wetland designs have been based on the design used for conventiona) ponds and land treatment systems. While the design of conventional systems is usually based on hydraulic residence time (and therefore water volume), some wetland treatment systems show a more consistent correlation with area and hydraulic loading rate than with hydraulic residence time (R. Kadlec, pers. comm.). This seems reasonable since a wetland is a shallow water system with large surface area in relation to its volume, and receives energy inputs (sun, rain, propagules, gases) on an area1 basis that is not related to volume. Also, because of the depth limits of wetland plants, the biomass of microbes attached to plants and sediments does not increase proportionally to depth except in a narrow range. The design guidelines presented in this Handbook are thus tentative.

Hydrologic factors in wetland design pertain to the volume of water, its reliability and extremes, and its movement through the site. Hydrologic considerations include climate and weather, hydroperiod, hydraulic residence time, hydraulic loading rate, groundwater exchanges (infiltration and exfiltration), losses to the atmosphere (evapotranspiration), and overall water balance.

CLIMATE AND WEATHER

Because wetlands are shallow water bodies open to the atmosphere, they are strongly influenced by climate and weather. Rainfall, snowmelt, spring runoff, drought, freeze, and temperature can all affect wetland treatment.

The high flows caused by heavy rains and rapid snowmelt shorten residence times. The efficiency of a wetland may therefore decrease during rainfall and snowmelt because of increased flow velocities and shortened contact times. High flows may dilute some dissolved pollutants while increasing the amount of suspended material as sediments in the wetland are resuspended and additional sediments are carried into the wetland by runoff. The first flush of runoff from a storm, often carries much higher pollutant concentrations than flows later in the storm. Taylor et al. (1993) found that intense storms during summer, when conditions were generally dry, often had greater impacts on treatment than storms during other times of the year, when conditions were generally wetter. Snowmelt and spring runoff can resuspend and export stored pollutants. Jacobson (1994) found that runoff during spring may carry more than half the annual nitrate and phosphorus exported during the year and suggests that wetland management should focus on this time of the year. Runoff in excess of maximum design flows should be diverted around the wetland to avoid excessive flows through the wetland.

Minimum temperatures limit the ability of wetlands to treat some, but not all, pollutants.. Wetlands continue to treat water during cold weather. However, freezing temperatures in winter and early spring can reduce treatment if the wetland either freezes solid or a cover of ice prevents the water from entering the wetland. If under-ice water becomes confined, water velocities may increase, thereby reducing contact times.

HYDROPERIOD

Hydroperiod is the seasonal pattern of water level fluctuations and is described by the timing, duration, frequency, and depth of inundation. The hydroperiod of a wetland results from the balance of inflow, outflow, and storage. Hydroperiod determines the availability of water throughout the year, the extreme wet and dry conditions that can be expected, the extent of storage and drainage that may be required, and the criteria to be used in designing the water control facilities. While hydroperiod can be engineered to control surface flow and to reduce its variability, the hydroperiod of a wetland will be strongly affected by seasonal differences in precipitation and evapotranspiration.

HYDRAULIC RESIDENCE TIME

The hydraulic residence time (HRT) of a treatment wetland is the average time that water remains in the wetland, expressed as mean volume divided by mean outflow rate. If short-circuiting develops, effective residence time may differ significantly from the calculated residence time.

HYDRAULIC LOADING RATE

Hydraulic loading rate (HLR) refers to the loading on a water volume per unit area basis. [loading = (parameter concentration)(water volume/area)].

GROUNDWATER EXCHANGE

The movement of water between a 'wetland add groundwater will affect the hydrology of the wetland. Constructed wetlands for domestic wastewater, agricultural wastewater, and mine drainage are usually lined to avoid-possible contamination of groundwater. If the wetland is properly sealed, infiltration can be considered negligible.

Many stormwater wetlands are sealed so that that water needed to support the wetland will be retained between storms. Other stormwater wetlands are designed to intercept groundwater to ensure sufficient baseflow. In this case, the wetland will receive groundwater when the water table is high and may discharge to groundwater when the water table is low.

EVAPOTRANSPIRATION

Evapotranspiration (ET) is the combined water loss through plant transpiration and evaporation from the water surface. In wetlands, the amount of surface area is large relative to the volume of water and ET is an important factor. Also, many wetland plants do not conserve water during hot, dry weather as most terrestrial plants do, and can transfer considerable amounts of water from a wetland to the atmosphere in summer. If ET losses exceed water inflows, supplemental water will be required to keep the wetland wet and to avoid concentrating pollutants to toxic levels.

Estimates of ET values vary widely. The Water Pollution Control Federation (1990) suggests that, for wetlands that are continuously flooded, ET can generally be estimated as being equal to lake evaporation, or approximately 70% to 80% of pan evaporation values. (Rainfall and pan evaporation data can be obtained from National Oceanic and Atmospheric Administration in Asheville, NC, or from local weather stations.) Kadlec (1993) found that dense stands of emergent vegetation reduced the total water loss from prairie potholes and concluded that the vegetation removed less water through transpiration than would have evaporated from open surface water. Other data indicate that most wetlands show ET to be equal to or slightly less than pan evaporation and that experiments that show higher ET rates have been conducted on too small a scale to compensate for edge effects.

WATER BALANCE

The overall water balance for a constructed wetland is an account of the inflow, storage, and outflow of water. Water inflow to the wetland includes surface water (the wastewater or stormwater), groundwater infiltration (in unlined wetlands), and precipitation: Storage is the surface water plus that in the pore spaces of the substrate. Outflow comprises evaporation from the water surface, transpiration by plants, effluent discharge, and exfiltration to groundwater. During design and operation, the wetland water balance is important for determining conformance with desired limits for HLR, hydroperiod range, HRT, and mass balances. A simple water balance equation for a constructed wetland is expressed as:

$$S = Q + R + I - O - ET \qquad (5.1)$$

Where: S = net change in storage
Q = surface flow, including wastewater or stormwater inflow,
R = contribution from rainfall
I = net infiltration (infiltration less exfiltration)
O = surface outflow
ET= loss due to evapotranspiration.

Equation 5.1 can be used to calculate water budgets for daily, monthly, or yearly intervals. Detailed water balances can be prepared with site-specific monitoring data collected during pilot- or full-scale operation of the wetland. If large seasonal variation is expected, monthly data are essential.

A number of factors can be used to manipulate the water budget:

- the volume of water released from the wetland can be varied
- evapotranspiration rates can be altered by shading, windbreaks, and the selection and management of ***vegetation*** around the wetland
- storage capacity can be adjusted with water control structures
- in SF wetlands, storage capacity can be increased by excavating deep pools or decreased by adding fill.

CHAPTER 6
SUBSTRATES

Wetland substrates support the wetland vegetation, provide sites for biochemical and chemical transformations, and provide sites for storage of removed pollutants. Substrates include soil, sand, gravel, and organic materials.

SOIL

Many soils are suitable for constructed wetlands. Soil properties that should be considered in selecting soils include cation exchange capacity (CEC), pH, electrical conductivity (EC), texture, and soil organic matter.

The pH of the soil affects the availability and retention of heavy metals and nutrients. Soil pH should be between 6.5 and 8.5. The EC of a soil affects the ability of plants and microbes to process the waste material flowing into a constructed wetland. Soils with an EC of less than 4 mmho/cm are best as a growth medium.

The surface area of the soil particles and 'the electrical charge on the surfaces of the soil particles account for much of a soil's activity., In the northeastern United States, most soils carry a net negative charge, thus providing electrostatic bonding sites for positively charged ions (cations), such as Ca^{2+}, Mg^{2+}, Fe^{2+}, $A1^{3+}$ and Mn^{2}. These cations on the soil surface can exchange with other cations in the soil solution, hence the term cation exchange. CEC measures a soil's capacity to hold positively charged ions and varies widely among different soils. The CEC of a soil that will be used as a planting medium should be greater than 15 meq/l00 g of soil.

The redox potential of the soil is an important factor in the removal of nitrogen and phosphorus. A reducing substrate must be provided to promote the removal of nitrate and ammonia. The removal of iron and manganese from mine water also requires a reducing environment.

A soil's capacity to remove and retain contaminants is a function of soil-water contact. Sandy or gravely soils have high K (porosity) values and water moves quickly through the soil. In contrast, the finer textures of silty or loamy soils promote longer soil-water contact. Flow through well-decomposed organic soils and most clays is slow.

The soil must provide enough organic matter. to fuel plant growth and mocrobial activity, particularly during startup. Wetlands are often built with infertile site soils, and organic amendments, such as compost, leaf litter, or sewage sludge, must be incorporated into the substrate.

Soil texture affects root growth and the retention of pollutants. Sandy, coarse-textured soils have a low potential for pollutant retention but little or no restriction on root growth. Thesesoils hold plants well but are low in nutrients. Additions of organic matter to coarse textured soils have been shown to improve plant survival and growth during the first several years while the organic litter is beginning to build up within the wetland. Medium textured or loamy soils are a good choice, as these soils have high retention of pollutants and little restriction on plant growth. Loamy soils are especially good because they are soft and friable, allowing for easy rhizome and root penetration. Dense soils, such as clays and shales, should be avoided because they may inhibit root penetration, lack nutrients, and have low hydraulic conductivities.

Soils with a high clay content aid in phosphorous retention but their low nutrient content may limit growth and development, although such soils may be suitable for wetlands used for nutrient-rich wastewaters, such as agricultural and domestic wastewaters. Organic admendments will be required. Soils with greater extractable aluminum have greater potential for phosphorous assimilation than do organic soils, making them well suited for domestic wastewater treatment. Highly organic soils enhance sulfate reduction and ionic adsorption and are well suited for mine drainage wetlands.

Although peats are common in natural wetlands, they are not the preferred soil for establishing constructed wetlands. Peats can release organic acids, which contribute to low pH. Also, when flooded, peats have a soft, loose texture that may not provide adequate support for plants.

The county soils maps, which are available through libraries or through the county NRCS offices, show the major soil types present and their relationship to site topography. The soils maps include a general description of the soil characteristics. However, the NRCS soils maps cannot be relied upon for detailed, site-specific information for several reasons:

- the NRCS data are averages and estimates tallied over many acres of ground
- most soils units include inclusions that may differ in significant ways from nearby soils
- soils vary with depth, that is, they are stratified. If the wetland is to be excavated, it is important to know the characteristics of the soil at the excavated depth.

Soils should ‘be analyzed before they are used in the wetland. Site-specific information on the hydraulic conductivity and permeability of the site soils must be made through field data collection. Laboratory soil analyses should include clay content and type of clay, percent organic matter, and mineral content.

SAND AND GRAVEL

Constructed wetlands receiving with water high in nutrients, such as domestic and agricultural wastewaters. can be built with sand or gravel. Sand is an inexpensive alternative to soil and provides an ideal texture for hand planting. Gravel can also be used. Many domestic sewage SSF wetlands in the United States have used media ranging from medium gravel to coarse rock. Sands and gravels dry out quickly and may need to be irrigated to maintain water levels while the vegetation is becoming established.

ORGANIC MATERIAL

Stabilized organic material, such as spent mushroom compost, sawdust, hay or straw bales, and chicken litter, have been used as organic substrates. Organic material provides a source of carbon to support microbial activity. Organic material also consumes oxygen and creates the anoxic environments that are required for some treatment processes, such as nitrate reduction and the neutralization of acidic mine drainage.

CHAPTER 7
VEGETATION

The function of plants in constructed wetlands is largely to grow and die: plant growth provides a vegetative mass that deflects flows and provides attachment sites for microbial development; death creates litter and releases organic carbon to fuel microbial metabolism. In addition, plants stabilize substrates while enhancing its permeability, and plants add greatly to the aesthetic value of the wetland. A dense stand of vegetation appears to moderate the effects of storms.

SELECTING PLANTS

The plants that are most often used in constructed wetlands are persistent emergent plants, such as bulrushes *(Scirpus),* spikerush *(Efeocharis),* other sedges (Cyperus). rushes *(Juncus),* common reed *(Phragrnites),* and cattails *(Typha).* Not all wetland species are suitable for wastewater treatment since plants for treatment wetlands must be able to tolerate the combination of continuous flooding and exposure to wastewater or stormwater containing relatively high and often variable concentrations of pollutants. A number of species that have been used successfully in the northeastern United States are listed in table 1.

For wastewater treatment wetlands, the particular species selected are less important than establishing a dense stand of vegetation. Any species that will grow well can be chosen. For stormwater wetlands, species should be chosen to mimic the communities of emergent plants of nearby natural wetlands. For both wastewater and stormwater wetlands, native, local species should be used because they are adapted to the local climate, soils, and surrounding plant and animal communities, and are likely to do well.

NRCS conservation agents and state personnel can recommend species for constructed wetlands.

SURFACE FLOW WETLANDS

In wetlands constructed to treat domestic sewage, agricultural wastewaters, and other wastewaters relatively high in organic matter, bulrushes (either softstem or common three-square) are often used because they are tolerant of high nutrient levels and because they establish readily but are not invasive. Arrowhead and pickerelweed have also been used successfully in agricultural wetlands. Blueflag iris can be planted along wetland edges to provide color. Cattails and common reed have been used frequently because of their high tolerances for many types of wastewater, but both have disadvantages. Cattails are invasive. Since cattail tubers are a favorite food of muskrats, cattails are susceptible to damage by muskrats. Also, Surrency (1963) found that cattails were subject to attack by insects similar to army worms and suggests that cattails may not be the best choice for agricultural wetlands. Common reed is a highly aggressive species that can eliminate other species once it is introduced. It produces abundant windborne seed and spreads readily to natural wetlands. It is becoming a problem in the Northeast and should not be used without approval from the regulatory agency.

For agricultural wastewater wetlands, the ammonia tolerances of the species must be considered. Wetland species vary in their ability to tolerate ammonia. Plants may be able to tolerate higher concentrations of ammonia if the plants are slowly acclimated to it.

For stormwater wetlands, the goal should be a diverse assemblage of plants. A diverse vegetation is aesthetically pleasing and may be more likely to resist invasive species, to recover from disturbance, and to resist pests than a less diverse stand. The numbers of wildlife attracted to a wetland generally increases as vegetation diversity increases.' The State of Maryland guidelines for stormwater wetlands suggest planting two primary species (some combination of arrowhead, common three-square, or softstem bulrush) and three other

Table 1. Emergent plants for constructed wetlands
(adapted from Schueler 1992 and Thunhorst 1993).

Recommended Species	Maximum Water Depth*	Notes
Arrow arum *Peltandra virginica*	12 inches	Full sun to partial shade. High wildlife value. Foliage and rootstocks are not eaten by geese or muskrats. Slow grower. pH: 5.0-6.5.
Arrowhead/duck potato *Saggitaria latifolia*	12 inches	Aggressive colonizer. Mallards and muskrats can rapidly consume tubers. Loses much water through transpiration.
Common three-square bulrush *Scirpus pungens*	6 inches	Fast colonizer. Can tolerate periods of dryness. High metal removal. High waterfowl and songbird value.
Softstem bulrush *Scirpus validus*	12 inches	Aggressive colonizer. Full sun. High pollutant removal. Provides food and cover for many species. of birds. pH: 6.5-8.5.
Blue flag iris *Iris versicolor*	3 - 6 inches	Attractive flowers. Can tolerate partial shade but requires full sun to flower. Prefers acidic soil. Tolerant of high nutrient levels.
Broad-leaved cattail** *Typha latifolia*	12-18 inches	Aggressive. Tubers eaten by muskrat and beaver. High pollutant treatment, pH: 3.0-8.5.
Narrow-leaved cattail** *Typha angustifolio*	12 inches	Aggressive. Tubers eaten by muskrat and beaver. Tolerates brackish water. pH : 3.7-8.5.
Reed canary grass *Phalaris arundinocea*	6 inches	Grows on exposed areas and in shallow water. Good ground cover for berms.
Lizard's tail *Saururus cernuus*	6 inches	Rapid grower. Shade tolerant. Low wildlife value except for wood ducks.
Pickerelweed *Pontedaria cordata*	12 inches	Full sun to partial shade. Moderate wildlife value. Nectar for butterflies. pH: 6.0-8.0.
Common reed** *Phragmites australis*	3 inches	Highly invasive; considered a pest species in many states. Poor wildlife value. pH: 3.7-8.0.

Recommended Species	Maximum Water Depth*	Notes
Soft rush *Juncus effusus*	3 inches	Tolerates wet or dry conditions. Food for birds. Often grows in tussocks or hummocks.
Spikerush *Eleocharis palustris*	3 inches	Tolerates partial shade.
Sedges *Carex* spp.	3 inches	Many wetland and several upland species. High wildlife value for waterfowl and songbirds.
Spatterdock *Nuphar luteum*	5 ft, 2 ft minimum	Tolerant of fluctuating water levels. Moderate food value for wildlife, high cover value. Tolerates acidic water (to pH 5.0).
Sweet flag *Acorus calamus*	3 inches	Produces distinctive flowers. Not a rapid colonizer. Tolerates acidic conditions. Tolerant of dry periods and partial shade. Low wildlife value.
Wild rice *Zizania aquatica*	12 inches	Requires full sun. High wildlife value (seeds, plant parts, and rootstocks are food for birds). Eaten by muskrats. Annual, nonpersistent. Does not reproduce vegetatively.

- These depths can be tolerated, but plant growth and survival may decline under permanent inundation at these depths.
- **Not recommended for stormwater wetlands because they are highly invasive, but can be used in treatment wetlands if approved by regulatory agencies

secondary species (see table 1) to enhance short- and long-term development and to reduce the invasion by undesirable plants such as common reed (Livingston 1989).

SubSurface Flow Wetlands

Many of the SSF constructed wetlands in the United States have used bulrush, common reed, cattail, or some combination of the three. About 40% of the operational SSF systems use only bulrush. Common reed has been widely used in British and European systems; however, it is a highly invasive species that can be very difficult to eradicate once started and a number of states now prohibit its use. Some SSF systems have been planted with a diverse vegetation similar to that of a natural marsh.

SOURCES OF PLANTS

Seeds, seedlings, entire plants, or parts of plants (rootstocks, rhizomes, tubers, or cuttings) can be used to establish wetland vegetation. While many wetland plants produce wind-borne seeds, vegetative spread by stolons and runners is common since seeds generally will not sprout under water. Many emergents have rhizomes, rootstocks, or tubers which, although they are primarily food storage organs, can generate new plants.

Seeds

Seeds are the least expensive but also the least reliable approach to planting. Seeds are generally broadcast on the saturated surface of the wetland. Seeds can also be scattered by shaking ripe spikes of plants over the wetland surface. Germination is unpredictable. Propagation by seeds requires an exposed, wet surface on which the seeds can germinate. Water levels can be raised as the plants grow, but the leaves must remain above water since the plants must be able to photosynthesize and transpire if they are to grow.

Seed stands are typically difficult to establish because scarification (abrasion of seed coat) and stratification (exposure to cold) requirements are largely unknown and because seeds are easily moved about by rain. However, many wetland species produce abundant wind-borne seed and will appear quickly on newly exposed surfaces if there is another wetland in the area to act as a source of seed.

Wetland Soil

The seeds of many wetland species remain viable for many years buried in sediments. Soil from a nearby wetland can be used as a source of plants since this soil will contain seeds of a number of native species that are well-adapted to local conditions. Approval must be obtained from the appropriate agency before removing wetland soil. Soil must not be taken from natural wetlands without a permit.

Cores (3 - 4 inch, or 8 - 10 cm, in diameter) of wetland soil from the donor marsh can be transplanted to the constructed wetland. Cores are excellent sources of seeds, shoots, and roots of various wetland plants and will promote the development of diverse wetlands. The disadvantages of soil cores are the time and cost associated with collecting, transporting, and planting the soil mass. Also, the soil is likely to contain propagules of undesirable, as well as desirable, species. If the cores are taken from a wetland dominated by a species that spreads by rhizomes (such as cattails), the resulting wetland will probably be dominated by that species since earthmoving cuts the rhizomes into pieces, each of which can produce a new plant.

Once in place, the soil should be kept moist, but not flooded, until the seeds germinate.

RhizoMes, Tubers, and Entire Plants

Plant materials include entire plants and plant parts, such as rhizomes and tubers. These materials are generally obtained from commercial nurseries or donor wetland sites (on-site nurseries or nearby constructed wetlands).

Plants should be obtained from local sources. The US Army Corps of Engineers (1993) recommends that plants should be transferred from areas within 100 miles latitude, 200 miles longitude, and 1,000 feet in elevation but notes that ecologists are expressing concern about the unknown consequences of relocating genetic stock to new areas. For example, plants become adapted to local pathogens, as well as beneficial mutualistic species, and their survival and growth are diminished when they are transplanted to different areas. The State of Florida now recommends a 50-mile radius for obtaining plants.

Locally-grown nursery stock is generally the most reliable and ecologically appropriate way to obtain plants. The NRCS Plant Materials Centers test and develop plants for various ‘applications and can provide plants. On-site nurseries established to provide plants for the project offer convenience, reliability, and low cost. Outdoor beds can be constructed at the-site of the construction project. The beds usually consist of pits 12 - 20 inches (30 - 50 cm) deep dug into the soil, lined with plastic film to prevent water loss, and partially filled with 8 - 12 inches (20 - 30 cm) of soil. Water inlets and outlets for the beds should be adjustable so that water levels can be varied to accommodate the different stages of germination and growth.

Rhizomes and tubers are usually collected in the late fall after growth has stopped or in early spring before new growth begins. The entire root system should be taken along with some soil. including the soil helps to inoculate the constructed wetland with microbes from the donor wetland.

Rhizomes generally are cut into lengths of two to three nodes, placed in moist peat or sand, and stored at cool temperatures (40°F, 4 - 5°C) until planting. Storage at cool temperatures stratifies the tubers and rhizomes (prepares them for growth) and enhances growth after spring planting. A common pitfall is to store plants under conditions that are too dry or too warm. Collecting plants in the spring and planting them immediately at the new site may reduce the mortality of rhizomes and rootstocks, but collection is more difficult because of the high water levels in most wetlands in the spring.

Manual collection is more common than machine collection, which is not practical unless large quantities of plants are needed or the project is a long-term one. Manual harvesting equipment includes modified garden tools, bags, buckets, and boats or canoes. Vegetative propagules are usually obtained by hand-digging whole plants and cutting apart roots, rhizomes, and tubers. At sites where water levels can be controlled, machinery can be used to dig underground parts.

Private wetland nurseries are becoming more widespread and can custom-propagate stock for wetlands if given enough advance notice. Some commercial nurseries will recommend species and will do the planting.

WHEN TO PLANT

In the Northeast, the planting period typically begins after dormancy has begun in the fall and ends after the first third of the summer growing period has passed. Fall dormant planting is recommended for tubers and rootstock and is very successful for bulrushes, rushes, and arrowhead. Sedges and cattails are grown more successfully in the spring after dormancy has been broken. Planting early in the spring growing season is generally successful. The NRCS Field Office Technical Guide (FOTG) or local nurseries can be consulted about planting times.

SITE PREPARATION

For SF wetlands, the site should be disked or harrowed to break up compacted soil once the wetland has been shaped and graded. The bed should then be shallowly flooded to settle the soil and level the bed. An extended settling period (a year or to the next growing season) should be provided, if possible. Constructed wetlands are often built in the fall and left flooded over the winter. The bed is then dewatered (but not completely dried) shortly before planting to produce a soft, moist soil.

HOW TO PLANT

Planting is usually done by hand. Few sophisticated planting techniques have been applied to wetland planting.

SURFACE FLOW WETLANDS

Dormant propagules, such as tubers and rhizomes, are planted by simply placing them deep enough in the substrate to prevent them from floating out of the medium. Approximately 1 - 2 inches (2 - 5 cm) of stem should be left on the tubers so the plants can obtain oxygen through the stem when the wetland is flooded. Tubers of arrowhead and softstem bulrush are often planted in this way.

For bareroot plants and tubers, a tree planting bar (dibble) or tile spade is a good tool. A slit is made in the substrate, the propagule inserted, and the slit sealed. The propagule must be planted deep enough to prevent it from floating out of the planting hole. For tall plants such as cattails, the stems should be broken over or cut back to 1 ft to prevent windthrow. Wetland cores and potted plants are placed in small holes dug with a shovel. Temporary anchoring may be needed if the substrate is' soft, the plants are buoyant, or erosion could disturb the existing system.

Vegetative propagules are usually spaced at 1 - 3 ft (0.3 - 1 m) intervals, depending on how rapidly the project must be completed. Clustered rather than ,uniform arrangements provide species and spatial diversity and better simulate a natural wetland. If the plants are planted in rows, running the rows perpendicular to the direction of flow will improve coverage and reduce channeling while the vegetation is filling in. When the plants have been placed, enough clean water should be added to maintain good saturation of the substrate, but not flood it. After new growth has reached 4 - 5 inches (10 - 12 cm), the water level can be raised. The water must not overtop the plants for extended periods or the plants will die.

SUBSURFACE FLOW WETLANDS

Most SSF wetlands are planted by hand. The use of individual root/rhizome material with growing shoots at least 8 inches (0.2 m) long is recommended. If mature, locally available plants are used, they can be separated into individual root/rhizome/shoot units containing root, rhizome, and shoot, with the mature stem cut back to <1 ft (<0.3 m) before planting.

The root/rhizome should be placed in the medium at a depth equal to the expected operational water level. The growing shoot should project above the surface of the media. To encourage deeper root penetration, some European systems lower the water level in the bed in the fall. In Europe, three years is necessary for the roots of common reed to reach their 2 ft potential depth. An alternative to lowering the water level in the entire wetland is to divide the system into two or more parallel cells and to alternate drawdown between the cells to encourage root penetration in the dormant cell.

ESTABLISHING AND MAINTAINING VEGETATION

In SF wetlands, 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 wetlands plants during the first growing season than too little because the plants do not receive adequate oxygen at their roots. For best survival and growth of small stalks (1 - 2 inches) during the first growing season, the substrate should only be saturated, not flooded. As the plants become well-established (2 - 3 months), water levels can be raised.

Mechanical protection may be needed to prevent animals from damaging newly established plants. Canada geese cause significant depredation by grazing on young shoots and seedlings and by uprooting rhizomes and tubers. Deer and black-birds can also damage newly established seedlings. Muskrats feed on the fleshy tubers of plants such as cattails and can quickly demolish a cattail wetland. Preventive methods include planting through chicken wire fence fastened over the surface of the substrate to prevent animals from excavating tubers and rhizomes.

Plantings should be allowed to become well established before the wastewater is introduced into the system since the plants need an opportunity to overcome the stress of planting before other stresses are introduced. The water must supply enough nutrients to support plant growth. If not, a solution of commercial nutrient supplement should be added. Satisfactory establishment may take from several months to one or two full growing seasons. The plants may not begin to reach maturity and equilibrium until late in the second growing season. A gradual rather than sudden increase in the concentration of the wastewater applied reduces shock to the vegetation. Alternatively, if plants are readily available and inexpensive, some die-off and replanting can be planned for in order to apply the wastewater sooner.

Water level management is key to maintaining wetland vegetation. Despite relatively broad depth tolerances, freshwater plants often sort by small variations in water depth, producing the apparent zonation of vegetation along the shores of marshes. Most wetland species are adapted to daily or seasonal fluctuations in water level but most wetland plants can tolerate neither extended periods of flooding nor drying of their roots.

Water quality also affects the health and survival of wetland plants. High nutrient loads, high or low pHs, high dissolved solids concentrations, and buildup of heavy metals and other toxics can affect the vegetation in wetlands. Constant pollutant loads work against species diversity and favor pollution-tolerant species such as cattails. In wetlands constructed to treat domestic wastewater and mine drainage, Kadlec (1989) and Webster et al. (1994) found that plant diversity declined and dominance by cattails increased as the wetlands aged.

Harvesting or winter burning of above-ground. biomass is sometimes used as a means of removing nitrogen and carbon and maintaining the wetland vegetation in a log (growth) phase of high physiological activity to enhance removal, but may disrupt the wetland and the maturation of the plant community. Decisions as to whether or not to harvest will depend on the objectives of the project and will be site-specific.

CHAPTER 8
CONSTRUCTION

Wetlands should be designed and constructed to provide reliability and 'safety. Standard engineering techniques should be used. It is important to use a skilled contractor since elevations must be accurate to assure proper hydraulic regimes, and compaction requirements must be met to control infiltration and exfiltration and to ensure berm stability. It is also important to have someone on site who is familiar with the plans, tolerances, and overall wetland objectives to answer the questions that always arise during construction.

CONSTRUCTION PLANS

Construction plans and specifications developed from treatment area requirements and siting investigations should be carefully reviewed. The level of detail depends on the size and complexity of the wetland, the physical characteristics of the site, and the requirements of the regulatory agencies. At a minimum, construction plans must have sufficient detail for accurate bid preparation and for construction.

A pre-bid conference with potential contractors is recommended to explain the concept, goals, and requirements of the project. This meeting can be effective in soliciting accurate bids from qualified contractors.

PRE-CONSTRUCTION ACTIVITIES

A preconstruction conference should always be held to interpret and explain the intent of the plans to the operator and the contractor. Many contractors who are experienced with other kinds of construction may have had little experience in building wetlands. Construction plans, specifications, and field layout must portray to the operator and the contractor the desired work. Because of wide variations in conditions and experience, plans may vary from very simple plans and a few stakes in the ground to complicated plans with detailed specifications and extensive staking. Pre-construction activities should be consistent with the size and complexity of the site and adequate to assure orderly and effective construction.

CONSTRUCTION ACTIVITIES

Construction includes building access roads; clearing; constructing basins and dikes; piping and valving; planting; and seeding. liming, fertilizing, and mulching dikes and disturbed areas. A valuable reference document for constructed wetlands is the *Engineering Field Handbook* (SCS 1992), especially Chapter 13: "Wetland Restoration, Enhancement. or Creation". EPA's 1993 publication *Wetland Creation and Restoration: Status of the Science*, Chapters 2, 3, 4, 13, and 17, is also recommended. Both are available through the National Technical Information Service (NTIS), US Department of Commerce, 5285 Royal Road, Springfield, VA, *22161;* telephone (703) 487 4650.

Use of the correct type and size of heavy equipment is crucial for proper and cost-effective construction. Under- and over-sized equipment can result in time and cost overruns. It is a good practice to show the equipment operator(s) the site during the planning stages to obtain his or her opinion on equipment, time requirements, and potential problems.

Construction must precisely follow the engineering plan 'if the system is to perform properly. If shallow sheet flow is desired, lateral bed slope should not vary by more than 0.1 ft from high spot to low spot since large slope or surface variations can cause channeling, especially in systems with high length-to-width ratios. Permeability specifications must be followed carefully to prevent leakage into or out of wastewater wetlands, if this is part of project specifications. If synthetic liners are required, installation should follow precisely the manufacturer's instructions for bedding material. sealing (liner-to-liner and liner-to-piping and control structures), and material placement on top of the liner.

SSF systems depend on high hydraulic conductivities in the substrate, and special provisions must be taken to avoid compacting and rutting of the substrate during construction. The importance of using low-ground-pressure equipment in the wetland and of controlling small machine or foot traffic to reduce compaction must be made clear to the contractor. Walk boards should be placed on the substrate during hand planting:

The hydraulic performance of both SF and SSF systems can be significantly influenced by improper construction, and short-circuiting of flow can often be traced to improper construction. In particular, SSF beds must be carefully constructed because of the heavy traffic involved in placing the rock or sand medium. In several cases, carefully graded beds were seriously disrupted when the trucks delivering the rock were allowed access to the beds during wet weather. One solution is to prohibit trucks from driving on the medium. Trucks should back in to unload at the edge of the area already covered. Subgrades can also be stabilized with geotextiles.

Muskrats and beavers can burrow into dikes or obstruct discharge pipes. Muskrat damage can be minimized or prevented by installing hardware cloth (metal screen) vertically in the dikes or by riprapping both upstream and downstream slopes. The initial cost is small compared to replacing the dike. If beavers are likely to be a problem, state wildlife personnel should be consulted to develop a plan to prevent their unwanted damming.

INSPECTION, STARTUP, AND TESTING

Before accepting the final product, the wetland should be flooded to design depth and all components, such as pumps and water control structures, should be thoroughly tested to ensure that they are operating properly and to check that water levels and flow distributions meet expectations.

During the initial operation, any erosion and channeling that develops should be eliminated by raking the substrate and filling by hand. Rills on the dike slopes and spillways should be filled with suitable material and thoroughly compacted. These areas should be reseeded or resodded and fertilized as needed. If there is seepage under or through a dike, an engineer should be consulted to determine the proper corrective measures. Startup of a new wetland system is a critical time. System startup comprises the filling and planting of the wetland and a period in which the soil/media, plants, and microbes adjust to the hydrologic conditions in the wetland. Like all living systems. wetlands are better able to tolerate change if they have been allowed time to stabilize initially.

After the initial stabilization period, a gradual increase in wastewater flow to allow the system to adjust to the new water chemistry is often wiser than immediately operating at the ultimate flow. In Europe, a full growing season is often allowed before wastewater is added. Much shorter stabilization periods (several weeks to several months) are typical in the United States. Wastewater should not be added until the plants have shown new growth, indicating that the roots have recovered from transplanting. Highly concentrated wastewaters, such as some agricultural wastes. will require a more gradual introduction than will less concentrated waters, such as stormwater or pre-treated sewage effluent.

CHAPTER 9
OPERATION, MAINTENANCE, AND MONITORING

OPERATION AND MAINTENANCE

Wetlands must be managed if they are to perform well. Wetland management should focus on the most important factors in treatment performance:

- providing ample opportunity for contact of the water with the microbial community and with the litter and sediment
- assuring that flows reach all parts of the wetland
- maintaining a healthy environment for microbes
- maintaining a vigorous growth of vegetation.

OPERATION AND MAINTENANCE PLAN

Operation and maintenance (O&M) should be described in an O&M plan written during the design of the constructed wetland system. The plan can be updated to reflect specific system characteristics learned during actual operation. The plan should provide a schedule for routine cleaning of distribution systems and weirs, dike mowing and inspection, and system monitoring. The plan should specify those individuals responsible for performing and paying for maintenance. The plan should address:

- setting of water depth control structures
- schedule for cleaning and maintaining inlet and outlet structures, valving, and monitoring devices
- schedule for inspecting embankments and structures for damage
- depth of sediment accumulation before removal is required
- operating range of water levels, including acceptable ranges of fluctuation
- the supplemental water source to be used to ensure adequate water levels during establishment and operation
- wastewater application schedule, if this is part of the system design. An application schedule should be selected that is both convenient and relatively continuous. Short, high-flow discharges to a wetland are more likely to erode or damage established vegetation than lower velocity, more continuous flows.
- scheduling discharges to or from the wetland, recycling/redirecting flows, or rotating between cells, if such are part of the design.

HYDROLOGY

In SF wetlands, water should reach all parts of the wetland surface. The wetland should be periodically checked to ensure that water is moving through all parts of the wetland, that buildup of debris. has not blocked flow paths, and that stagnant areas have not developed. The importance of assuring adequate water depth and movement cannot be over-emphasized. Stagnant water decreases removal and increases the likelihood of mosquitoes and unsightly conditions. Flows and water levels should be checked regularly.

SSF wetlands should be checked to see that surface flow is not developing.

STRUCTURES

Dikes, spillways, and water control structures should be inspected on a regular basis and immediately after any unusual flow event. Wetlands should be checked after high flows or after rapid ice break-up; both can scour substrates, particularly at outlets. Any damage, erosion, or blockage should be corrected as soon as possible to prevent catastrophic failure and expensive repairs.

VEGETATION

Water level management is the key to determining the success of vegetation. While wetland plants can tolerate temporary changes in water depth, care should be taken not to exceed the tolerance limits of desired species for extended periods of time. Water depth can be increased during the cold months to increase retention time and to protect against freezing. Alternating flows and drawdown may help to oxidize organic matter and to encourage the recruitment of new plants into the wetland. Vegetative cover on dikes should be maintained by mowing, and fertilizing or liming, as needed. Frequent mowing encourages grasses to develop a good ground cover with extensive root systems that resist erosion, and prevents shrubs and trees from becoming established. The roots of shrubs and trees can create channels and subsequent leakage through the berm.

Vegetation should de inspected regularly and. invasive species should be removed. Herbicides should not be used except in extreme circumstances, and then only with extreme care, since they can severely damage emergent vegetation.

MUSKRATS.

Muskrats and other burrowing animals can damage dikes and liners. If wire screening was not installed in the dikes, a thick layer of gravel, rock, or bentonite over trouble spots may inhibit burrowing. If damage continues, the animals may have to be trapped and removed for temporary relief until wire screen can be installed. Burrows can also be sealed by placing bentonite clay in the entryway and adding water to the bentonite to seal the opening.

MOSQUITOES

Mosquitoes are common in natural wetlands and can be expected in constructed wetlands. However, in the mid- atlantic states, mosquitoes are usually not a major problem in constructed wetlands.

The best approach to avoiding mosquito problems in constructed wetlands is to create conditions in the wetland that are not attractive to mosquitoes or are not conducive to larval development. Open, stagnant water creates excellent mosquito breeding habitat, and stagnant, high nutrient water is ideal for larval development. Flowing water and a covered water surface minimize mosquito development.

Control methods include unblocking flows to eliminate stagnant backwaters, shading the water surface (females avoid shaded water for egg-laying). and dispersing floating mats of duckweed or other floating plants.

Purple martins, swallows, and bats can eat thousands of adult mosquitoes every day, so providing purple martin houses, swallow perches, and bat boxes will reduce the number of mosquitoes.

Mosquitofish *(Gambusia)* can be introduced to prey on mosquito larvae. The green sunfish *(Lepornis cyanellus),* a native. hardy, and aggressive mosquito-eating fish, can be used in areas that are too cold for mosquitofish. Some control is provided by the larvae of insects. such as dragon-. flies, which prey on mosquito larvae.

The control of mosquitoes with insecticides, oils, and bacterial agents such as Bti *(Bacillus thuringiensis isroelensis)* is often difficult in constructed wetlands. The use of insecticides in constructed wetlands with large amounts of organic matter is ineffective because the insecticides adsorb onto the organic matter and because they are rapidly diluted or degraded by the water traveling through the wetland. Chemical treatment should be used with caution because it is poorly understood and runs the risk of contaminating both the wetland and the receiving stream. Before beginning any involved control procedures, every aspect of the wetland system and the surrounding area should be carefully inspected, perhaps with the aid of a good vector control specialist. The inspection should include such minor components as old cans, discarded tires, undrainable depressions in wooded areas, hollow stumps, water control structures, open piping, and anywhere else that standing water can accumulate. Mosquito problems often originate from some small and frequently overlooked pocket of standing water rather than from the wetland as a whole.

MONITORING

Monitoring is an important operational tool that:

- provides data for improving treatment performance
- identifies problems
- documents the accumulation of potentially toxic substances before they bioaccumulate
- determines compliance with regulatory requirements.

Monitoring is needed to measure whether the wetland is meeting the objectives of the wetland system and to indicate its biological integrity. Monitoring the wetland can identify problems early on, when intervention is most effective. Photographs can be invaluable in documenting conditions. Photographs should be taken each time at the same locations and viewing angles.

The level of detail of the monitoring will depend on the size and complexity of the wetland system and may change as the system matures and its performance becomes more well known. As a minimum. lightly-loaded systems that have been operating satisfactorily may only need to be checked every month and after every major storm. Those that are heavily loaded will require more frequent and detailed monitoring.

MONITORING PLAN

A written monitoring plan is essential if continuity is to be maintained throughout the life of the project, which may span many decades. The monitoring plan should include:

- clearly and precisely stated goals of the project
- the specific objectives of monitoring
- organizational and technical responsibilities
- tasks and methods
- data analysis and quality assurance procedures
- schedules
- reporting requirements
- resource requirements
- budget.

MONITORING FOR DISCHARGE COMPLIANCE

Monitoring for compliance with the limitations of the discharge permit represents the minimum of sampling and analysis a requirements. A fixed weir at the outlet provides a simple means of measuring flow and collecting water samples. The parameters to be monitored and the frequency of data collection will be set by the terms of the permit.

MONITORING FOR SYSTEM PERFORMANCE

Wetland system performance is usually assessed by determining:

- hydraulic loading rates
- inflow and outflow volumes
- water quality changes between inflow and outflow
- excursions from normal operating conditions.

The effectiveness of contaminant removal can be determined from the difference between influent loads (inflow volume x contaminant concentration) and effluent loads (discharge volume x contaminant concentration). The parameters of concern may include:

- domestic wastewater: BOD,, nitrogen, phosphorus, total suspended solids, heavy metals, bacteria (total or fecal coliform)

- agricultural wastewater: BOD,, nitrogen, phosphorus, total suspended solids, pesticides, bacteria (total or fecal coliform)
- mine drainage: pH, iron, manganese, aluminum, total suspended solids, sulfate
- stormwater: total suspended solids, nitrogen, phosphorus. heavy metals, vehicle emission residues

Surface water sampling stations should be located at accessible points at the inlet and outlet, and, depending on the size and complexity of the system, at points along the flow path within the wetland. Surface water quality stations should be permanently marked. Boardwalks can be installed to avoid disturbing sediment and vegetation while sampling. If the wastewater could contain toxic pollutants, such as pesticides or heavy metals, sediments should be sampled once or twice a year to monitor the potential buildup of contaminants in the wetland sediments. The effluent should be sampled during high storms and high spring runoff flows to assure that sediments are being retained in the wetland. Groundwater should also be monitored once ***or*** twice a year to ensure that the wetland is not contaminating groundwater.

Monitoring for Wetland Health

The wetland should be checked periodically to observe general site conditions and to detect major adverse changes, such as erosion or growth of undesirable vegetation. Vegetation should be monitored periodically to assess its health and abundance. For wetlands that are not heavily loaded, vegetation monitoring need not be quantitative and qualitative observations of the site will usually suffice. Large systems and those that are heavily loaded will require more frequent, quantitative monitoring. In general, more frequent monitoring also is required during the first five years after the wetland is installed.

Species composition and plant density are easily determined, by inspecting quadrats (square plots, usually 3 ft x 3 ft) within the wetland at selected locations. A lightweight, open frame of wood or PVC pipe is laid on the wetland and the number of stems of each species present within the frame is counted. Changes of concern include an increase in the numbers of aggressive nuisance species, a decrease in the density of the vegetative cover, or signs of disease.

The vegetation in constructed wetlands is subject to gradual year-to-year change, just as in natural wetlands. There may be tendency for some species to die out and be replaced by others. Temporary changes, such as the appearance of duckweed or algae, can occur in response to random or seasonal climatic changes. Because vegetative changes are often slow, they may not be obvious in the short-term, and good record-keeping becomes essential.

The buildup of accumulated sediment and litter decreases the available water storage capacity, affecting the depth of the water in the wetland and possibly altering flow paths. Sediment, litter, and water depths should be checked occasionally.

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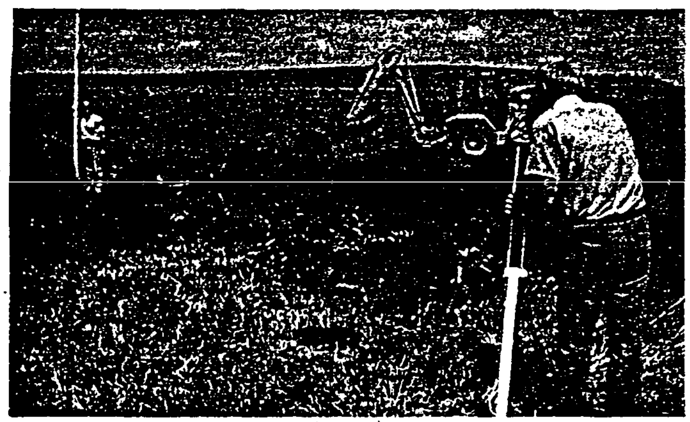
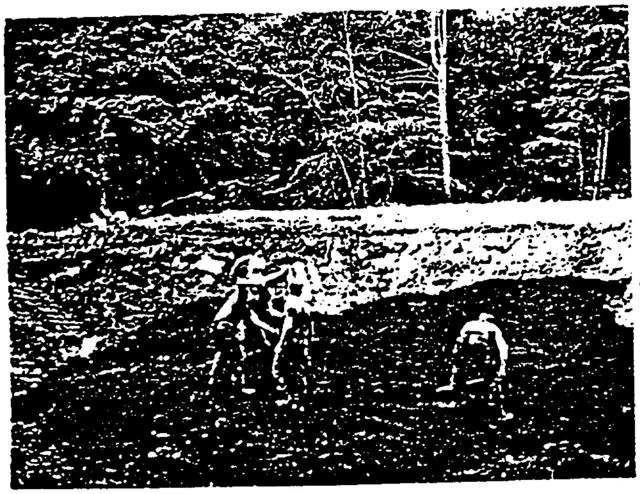
1. Constructed wetlands, such as this stormwater wetland, provide aesthetics and wildlife habitat as well as water quality improvement and stormwater control.

2. Constructed wetlands are a cost-effective means of removing metals from mine drainage. The black deposits are manganese precipitates.

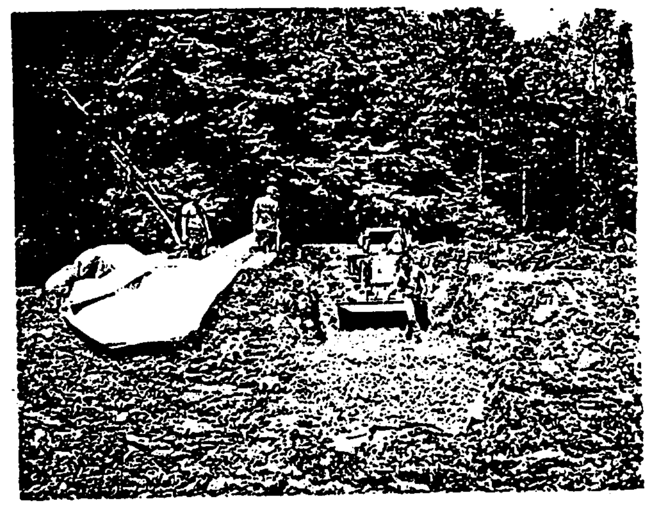


3. Site surveys are necessary for proper design and construction.

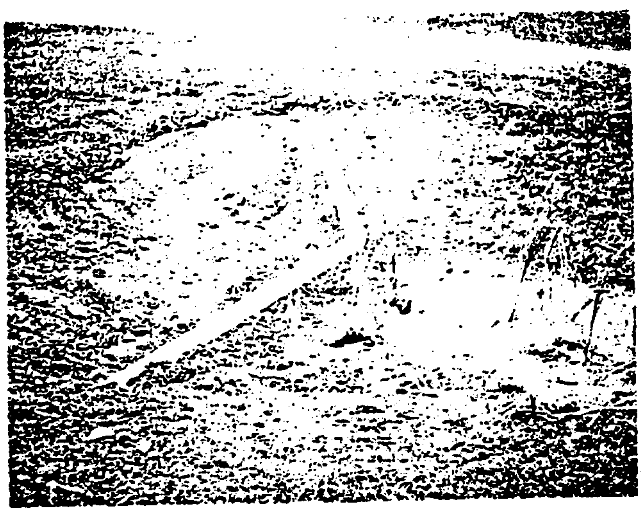
4. Including a deeper, open water area increases the wildlife value of the wetland and may increase ammonia removal.



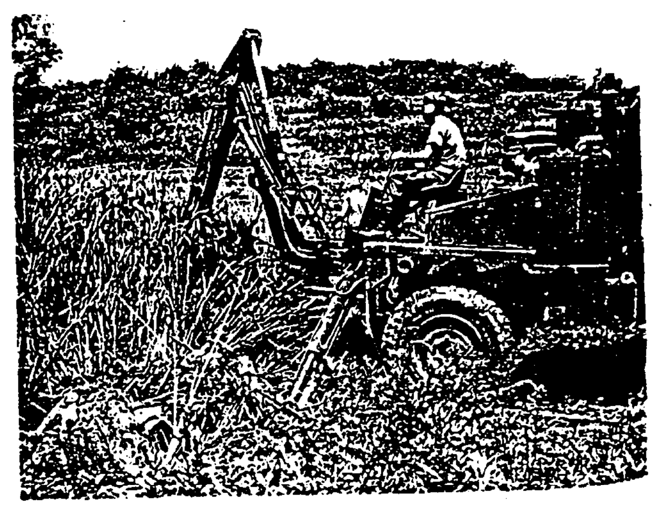
5. An organic substrate is often used for wetlands that will treat coal mine drainage.



6. This anoxic limestone drain, which is being built with the help of the National Guard, will add alkalinity to acidic drainage from an abandoned coal mine before wetland treatment.

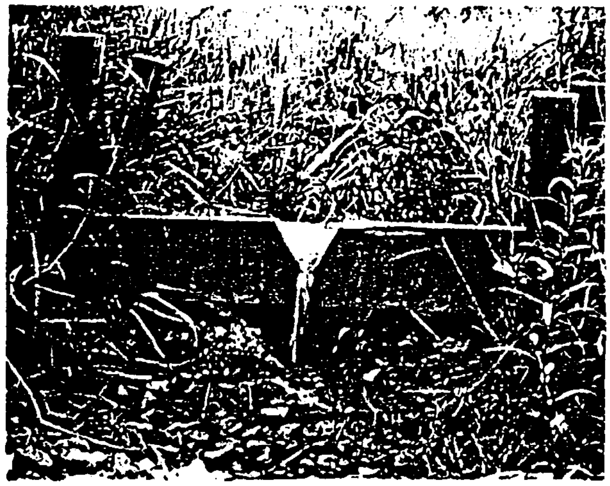


7. Perforated inlet pipes are a simple way to distribute wastewater across the width of the cell.

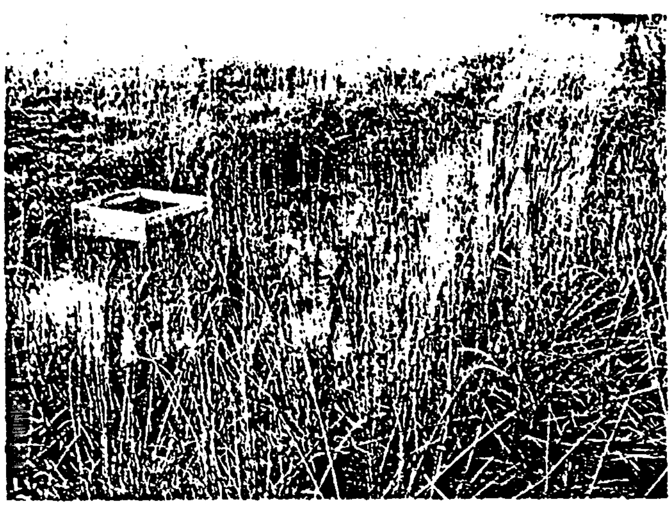


8. Construction usually requires heavy equipment.

9. Straw bales can be used to create long flow paths as part of the initial design, as here, or they can be added later to correct short-circuiting.



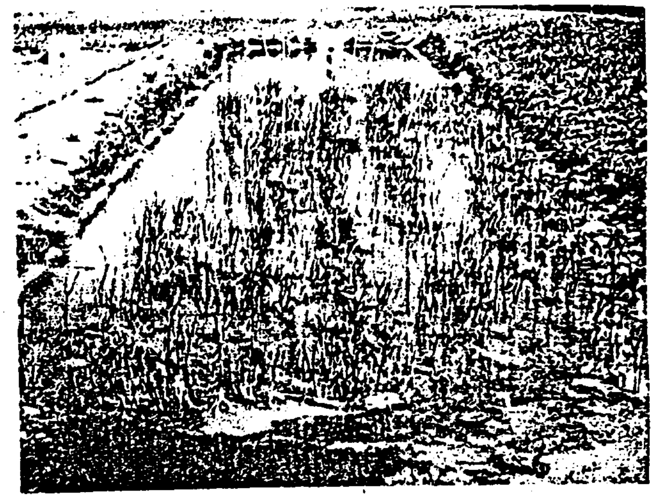
10. A V-notch weir is simple to construct but- does not allow water levels to be adjusted easily.



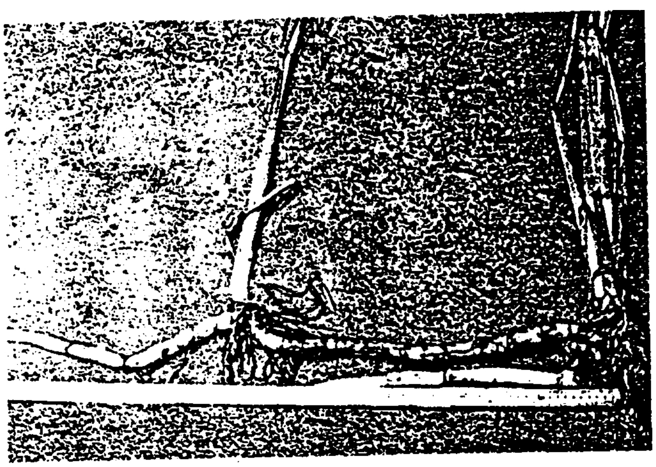
11. Structures may need to be protected from vandals and animals.

12. After excavation, grading, and compaction. a newly-constructed wetland is ready for planting.

13. After flooding the wetland to settle the substrate, the wetland should be drained for planting.



14. Water levels can be raised gradually as the plants grow.



15. A cattail rhizome.

16. Dense vegetation promotes sedimentation and pollutant removal.

NOTES

NOTES

abiotic .... not involving biological processes
aerobic .... requiring free oxygen
algae .... primitive green plants that live in wet environments
ALD.......................... anoxic limestone drain
AMD .... acidic mine drainage
AML.......................... abandoned mine lands
anaerobic .... a situation in which molecular oxygen is absent; lacking oxygen
anoxic .... without free oxygen
aquifer.......................... a permeable material through which groundwater moves
aspect .... the ratio of length to width
AWMS .... animal waste management system
baseflow.......................... the portion of surface flow arising from groundwater; the between-storm Bow
biomass .... the mass comprising the biological components of a system
biotic .... the living parts of a system; biological
BMP .... Best Management Practice
BOD .... biochemical oxygen demand, often measured as 5-day biochemical oxygen demand (BOD_5); the consumption of oxygen by biological and chemical reactions
CEC .... cation exchange capacity
community (plant) ..... the assemblage of plants that occurs in an area at the same time
denitrification .... the conversion of nitrate to nitrogen gas, through the removal of oxygen
detritus .... loose, dead material; in wetlands, largely the leaves and stems of plants
emergent wetland....... a wetland dominated by emergent plants, also called a marsh
EC .... electrical conductivity
effluent .... the surface water flowing out of a system
emergent plant .... a non-woody plant rooted in shallow water with most of the plant above the water surface
ET .... evapotranspiration
evapotranspiration ..... loss of water to the atmosphere by evaporation from the water surface and by transpiration by plants
exfiltration .... the movement of water from a surface water body to the ground
exotic species .... not native; introduced
HLR.......................... hydraulic loading rate: loading on a unit area basis
HRT .... hydraulic residence time; average time that moving water remains in a system
hydric soil .... a soil that is saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper part of the soil
hydrolysis .... chemical decomposition by which a compound is resolved into other compounds by taking up the elements of water
bydroperiod .... the seasonal pattern of changes in water level
infiltration .... the movement of water from the ground into a surface water body
influent .... the surface water flowing into a system
karst .... irregular, pitted topography characterized by caves, sinkholes, and disappearing streams and springs, and caused by dissolution of underlying limestone, dolomite, and marble
marsh .... an emergent wetland
microbe .... microscopic organism; includes protozoa, bacteria, yeasts, molds, and viruses

microorganism .... term often used interchangeably with microbe

native species .... one found naturally in an area; an indigenous species

nitrification .... the conversion of ammonia to nitrate through the addition of oxygen

non-persistent plant . . . a plant that breaks down readily after the growing season

non-vascular plant ..... a plant without differentiated tissue for the transport of fluids; for instance, algae

NPS .... nonpoint source

organic matter .... matter containing carbon

oxidation .... the process of changing an element from a lower to a higher oxidation state by the removal of an electron(s) or the addition of oxygen

pathogen .... a disease-producing microorganism

peat .... partially decomposed plant material, chiefly mosses

perennial plant .... a plant that lives for many years

permeability .... the capacity of a porous medium to conduct fluid

persistent plant .... a plant whose stems remain standing from one growing season to the beginning of the next

redox .... reduction/oxidation

reduction .... the process of changing an element from a higher to a lower oxidation state, by the addition of an election(s)

rhizome .... a root-like stem that produces roots from the lower surface and leaves, and stems from the upper surface

riparian .... pertaining to the bank of a stream, river, or wetland

SAPS .... successive alkalinity-producing system

SF .... surface flow

SSF .... subsurface flow

stolon .... a runner that roots at the nodes

scarification .... abrasion of the seed coat

stratification .... treatment of seed by exposure to cold temperatures

succession .... the orderly and predictable progression of plant communities as they mature

transpiration .... the process by in which plants lose water

tussock .... a hummock bound together by plant roots, especially those of grasses and sedges

tuber .... a short thickened underground stem having numerous buds or “eyes”

TSS .... total suspended solids

vascular plant .... a plant that possesses a well-developed system of conducting tissue to transport water, mineral salts, and foods within the plant

wrack .... plant debris carried by water

ABBREVIATIONS AND CONVERSION FACTORS

MULTIPLY	BY	TO OBTAIN
ac, acre	0.4047	ha, hectare
cfs, cubic foot per second	440.831	gpm, gallon per minute
cfs, cubic foot per second	$2.8317 \times l0^{-2}$	m^3/s, cubic meter per second
cm, centimeter	0.3937	inch
cm/sec, centimeter per second	3.28×10^{-2}	fps, foot per second
^{o}F, degree Fahrenheit	5/9 (^{0}F - 32)	^{o}C, degree Celsius
ft, foot	0.305	m, meter
ft^2, square foot	9.29×10^{-2}	m^2, square meter
ft^3, cubic foot	$2.83 \times l0^{-2}$	m^3, cubic meter
ft/mi, foot per mile	0.1895	m/km, meter per kilometer
fps, foot per second	18.29	m/min, meter per minute
g/m^2/day, gram per square meter per day	8.92	lb/ac/day, pound per acre per day
gal, gallon	3.785	L, liter
gal, gallon	3.765×10^{-3}	m^3, cubic meter
gpm, gallon per minute	$6.308 \times l0^{-2}$	L/s. liter per second
ha, hectare	2.47	ac, acre
inch	2.54	cm, centimeter
kg, kilogram	2.205	lb, pound
kg/ha/day, kilogram per hectare per day	0.892	lb/ac/day, pound per acre per day
kg/m^2, kilogram per square meter	0.2	lb/ft^2, pound per square foot
L, liter	3.531×10^{-2}	ft^3, cubic foot
L, liter	0.2642	gal, gallon
lb, pound	0.4536	kg, kilogram
lb/ac, pound per acre	1.121	kg/ha, kilogram per hectare
m, meter	3.28	ft, foot
m^2, square meter	10.76	ft^2, square foot
m^3, cubic meter	1.31	yd^3, cubic yard
m^3, cubic meter	264.2	gallon, gal
m^3/ha/day, cubic meter per hectare per day	106.9	gallon per day per acre, gpd/ac
mm, millimeter	$3.94 \times l0^{-2}$	inch
mi, mile	1.609	kilometer, km

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