

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 applica-

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 Pollu-
tion 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

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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

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
- they create 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, and 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.

A N I M A L S

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

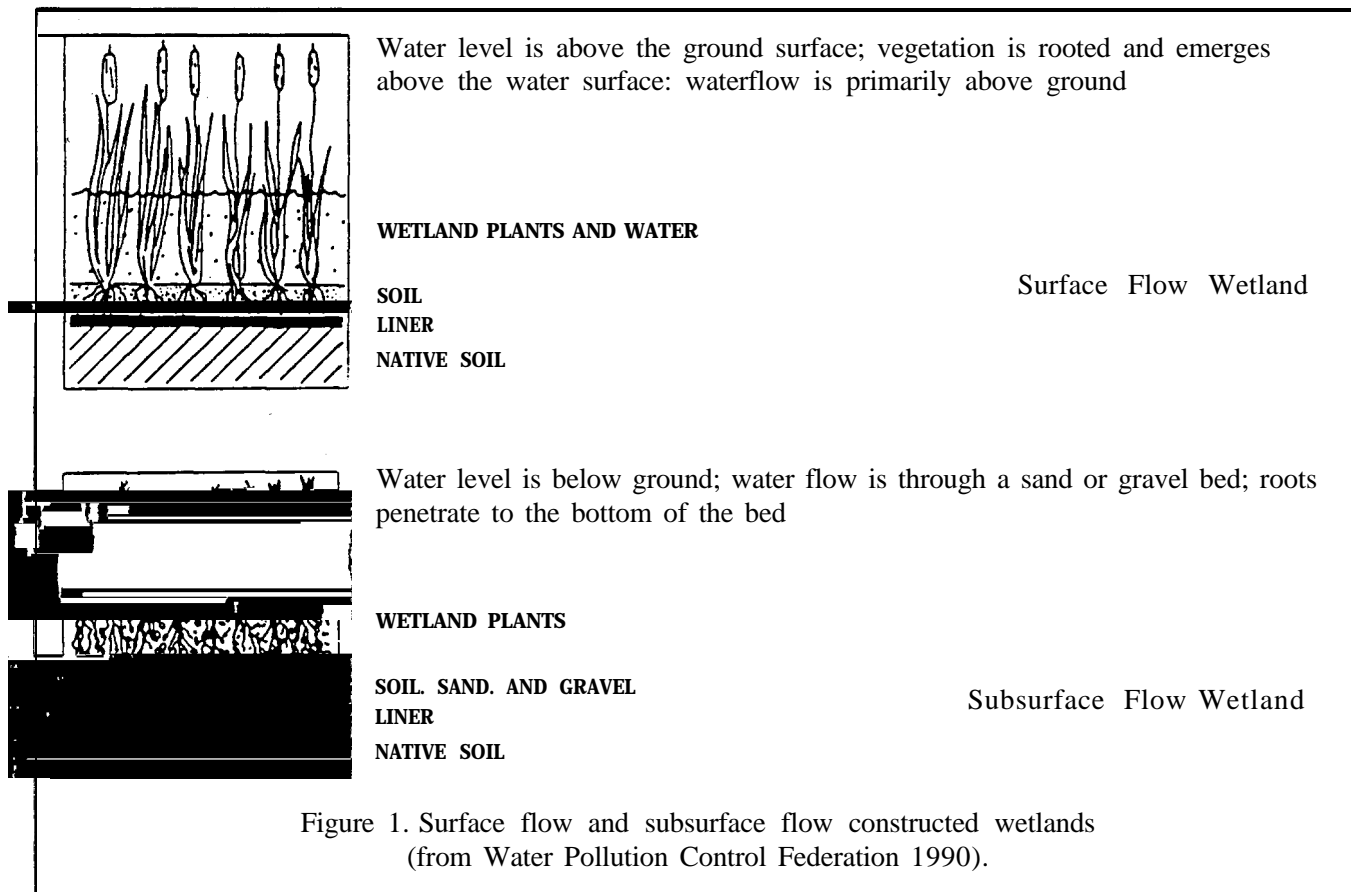
performance may be less consistent than in conventional treatment. Wetland treatment efficiencies may vary seasonally in response to changing environmental conditions, including rainfall and drought. While the average performance over the year may be acceptable, wetland treatment cannot be relied upon 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.



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

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,

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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.

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.

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 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 NWI 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 NWI information should be field-checked by a wetlands scientist. Historical aerial photography,

PERMITS AND REGULATIONS

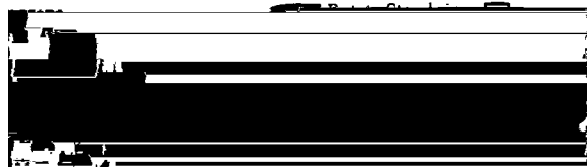
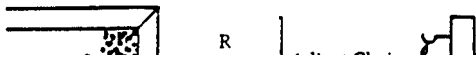
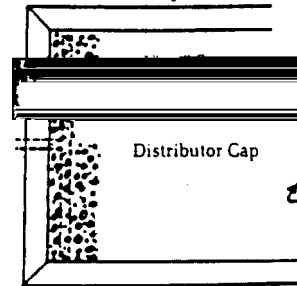
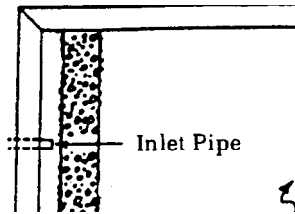
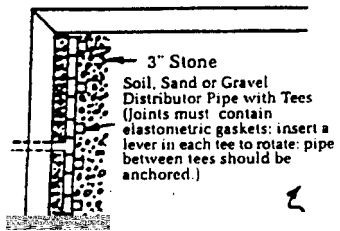
The appropriate agency(ies) must be contacted to determine the regulatory requirements for a proposed constructed wetland and its discharge. Work in a waterway or natural wetland requires a permit. Discharges to natural waters also require a permit. In some zoned communities, zoning approval may be required.

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),



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

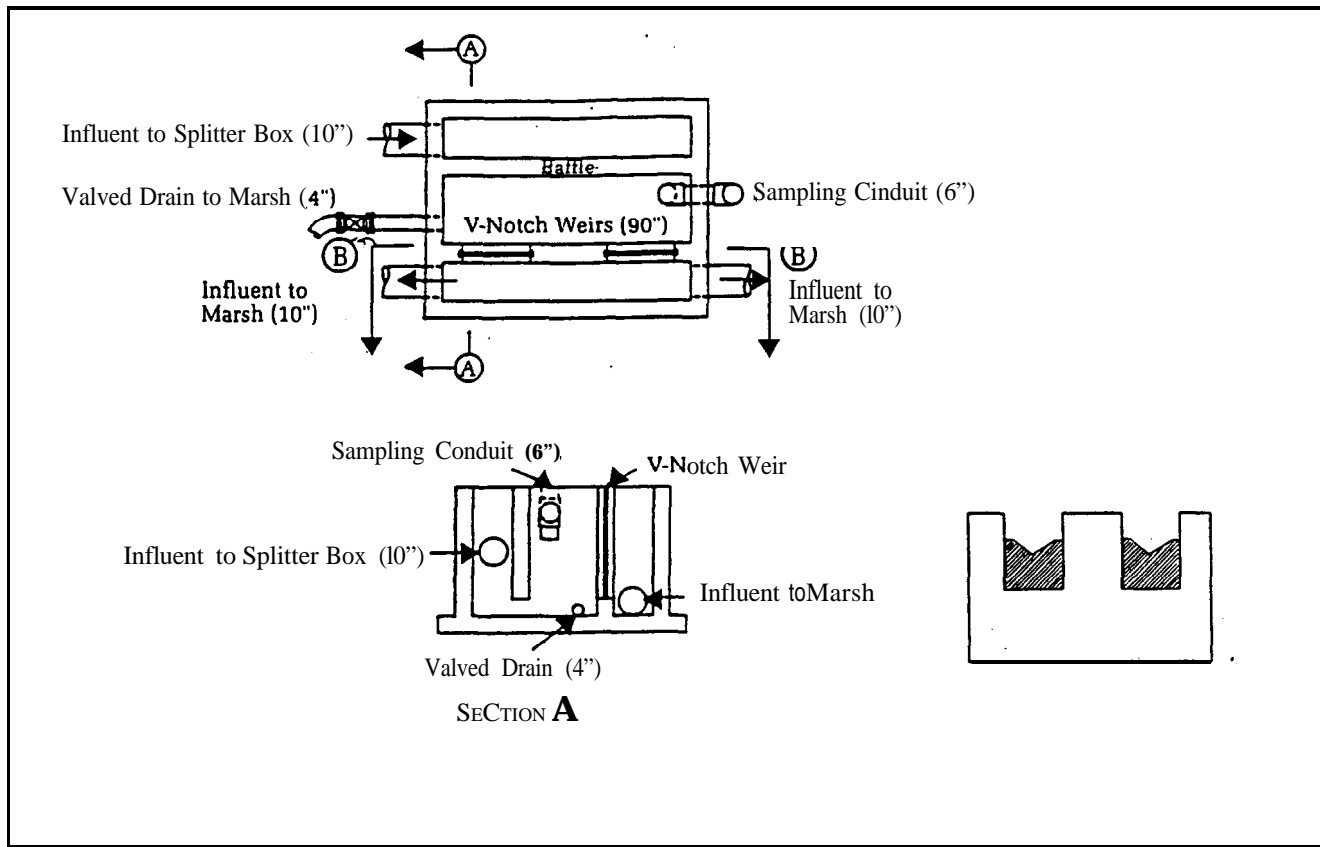
Inlet structures at SSF systems include surface and subsurface manifolds, open trenches perpendicular to the direction of flow, and simple single-point weir boxes. A subsurface manifold avoids the buildup of algal slimes and the consequent clogging that can occur next to surface manifolds, but is difficult 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-



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 (<12 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

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 conventional 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 areal 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

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 and 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.

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:

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

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

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 (*Phragmites*), 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 **F**LOW 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).

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 materi-

als 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 a Th2.42.421

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 W

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

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.

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
- |

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

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

- 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

- | 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

plots, usually 3 ft x 3 ft) within the wetland at selected locations. A lightweight, open frame of wood or

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

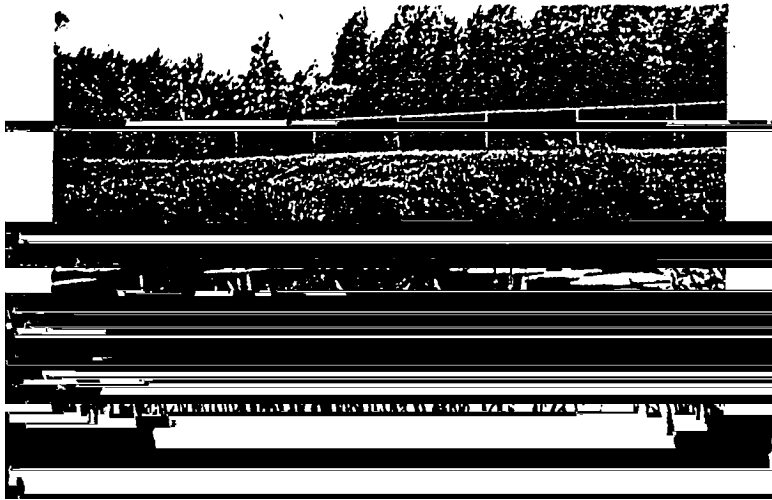
The wetland should be checked periodically to observe general site conditions and to detect major adverse changes, such as erosion or growth of undesirable vegetation. Vegetation should be monitored periodically to assess its health and abundance. For wetlands that are not heavily loaded, vegetation 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.

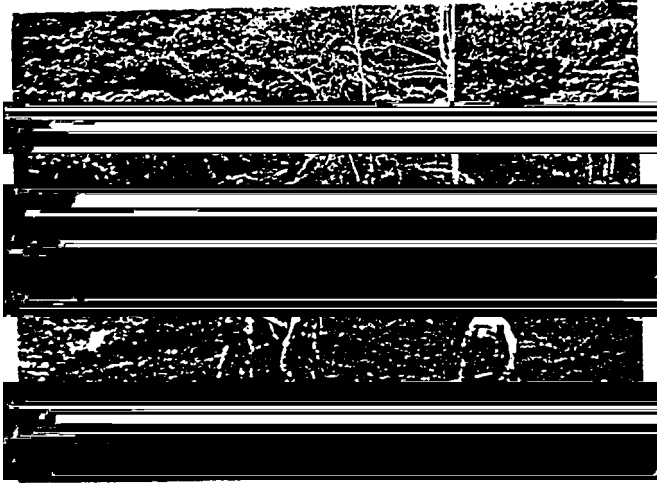
Species composition and plant density are easily determined, by inspecting quadrats (square

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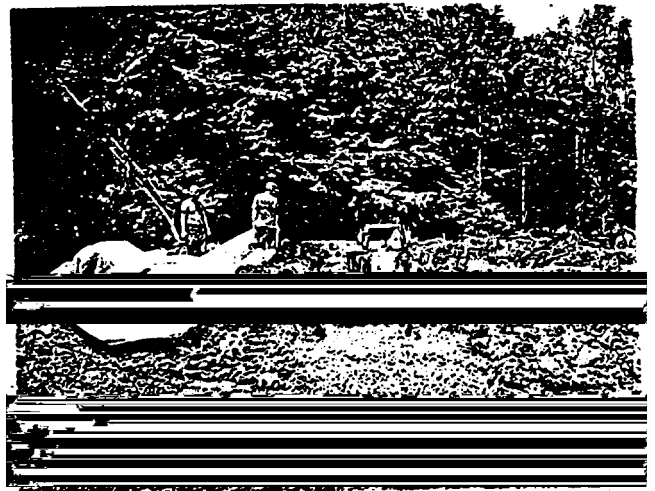


5. An organic substrate is often used for wetlands that will treat coal mine drainage.

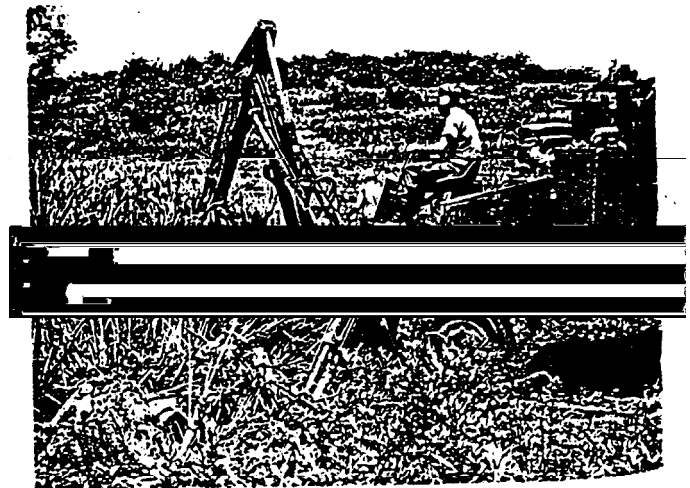


7. Perforated inlet pipes are a simple way to distribute wastewater across the width of the cell.

8. Construction usually requires heavy equipment.



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.







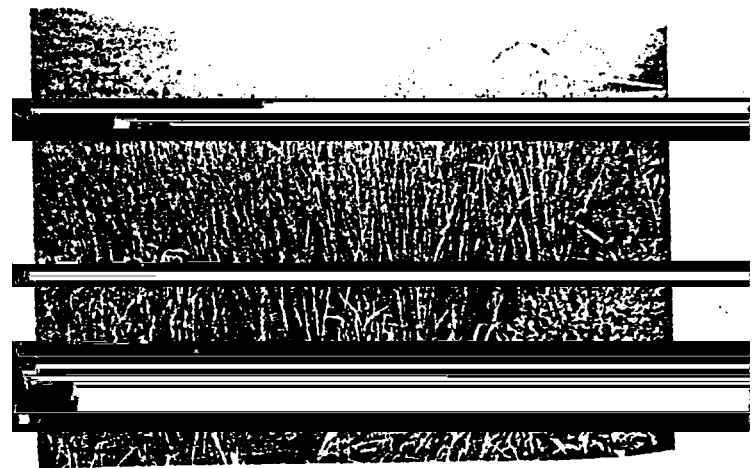
13. After flooding the wetland to settle the substrate, the wetland should be drained for planting.



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

GLOSSARY

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 flow
biomass	the mass comprising the biological components of a system

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 electron(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

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	2.8317×10^{-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
°F, degree Fahrenheit	$5/9 (°F - 32)$	°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	2.83×10^{-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	6.308×10^{-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	y d 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	3.94×10^{-2}	inch
mi, mile	1.609	kilometer, km

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