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Chapter 3 Constructed Wetlands

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637.0300 Introduction

(a) Purpose and scope

The constructed wetland is a shallow, earthen impoundment containing hydrophytic vegetation designed to treat both point and nonpoint sources of water pollution. Its principal physical components include the aquatic vegetation, substrate for plant and microbial growth, the basin itself, associated structural devices for water management, and the water that flows through the system. The treatment mechanisms are a complex mix of physical, chemical, and biological processes.

This chapter focuses on constructed wetlands used to treat wastewater from confined livestock operations. It addresses the types of waste treatment wetlands, treatment processes, role of vegetation, benefits and concerns, planning considerations, design procedures, and operation and maintenance requirements.

(b) Background

Constructed wetlands have been used for treating municipal, industrial, and mining wastewater for decades. The earliest reported wetland used to treat animal waste in this country was at a beef feedlot in Iowa, which began operation in the 1930s. It was not until the late 1980s and early 1990s, however, that animal waste constructed wetlands came into vogue, with the earliest ones installed in Kentucky, Alabama, and Mississippi.

In 1991, the Natural Resources Conservation Service (NRCS) (then the Soil Conservation Service) developed technical guidelines for the design of constructed wetlands (CWs) used to treat wastewater from livestock facilities (USDA 1991). The design criteria in that document were based on state-of-the-art information at that time.

In 1997, the Environmental Protection Agency's (EPA) Gulf of Mexico Program (GMP) sponsored publication of a literature review, database, and research synthesis on animal waste constructed wetlands throughout the United States and Canada (CH2M-Hill and Payne Engineering 1997). The Livestock Wastewater Wetland database presents information from more than 70 sites including pilot and full-scale facilities.

Evaluation of the database revealed that only part of the many installed systems in this country have been thoroughly monitored. However, enough information has been provided to allow development of new design criteria for animal waste systems. These data have been analyzed in light of treatment wetland performance models that were originally developed for municipal wastewater. Performance data from testing of constructed wetlands treating wastewater for livestock operations have been used to calibrate those models and allow performance estimation based on flow rates and pollution concentrations. Those models and parameters are described in this chapter for design of new constructed wetlands.

637.0301 Types of constructed wetlands

Three principal types of constructed wetlands have been used for treating wastewater. They include surface flow (SF), subsurface flow (SSF), and floating aquatic plant (FAP) systems. Figure 3–1 provides cross sectional drawings of these wetland types.

Natural wetlands have been used to treat municipal wastewater; however, they are not used for animal waste treatment because of the complexity of design, the difficulty of obtaining necessary permits, and the risk of degrading natural wetland resources. Therefore, only the three principal types will be described here.

(a) Surface flow wetlands

SF wetlands are used throughout the world to treat municipal wastewater and are the most commonly used wetland type in North America. The SF wetland was the only one recommended by NRCS for the treatment of livestock facility wastewater in its technical guidelines issued in 1991 (USDA NRCS 1991). It still remains the primary choice for treatment of animal waste for reasons presented here.

SF wetlands are shallow, earthen basins planted with rooted, emergent wetland vegetation. Water flows across the surface at depths that typically range from 6 to 18 inches, depending on the type of vegetation and other design factors. The bottom slope must be flat from side to side, but may be flat or have a slight gradient from inlet to outlet.

Much of the treatment results from the activities of microorganisms, principally bacteria and fungi, that thrive in this type of wetland environment. Many of the organisms become attached to submersed plant stems and litter, while others become part of the soil/plant-root matrix. In addition, the entire water column is alive with microorganisms that contribute to the treatment process.

Wastewater in the SF wetland flows across the surface of the bed and is visible. Consequently, it is sometimes called a free water surface (FWS) wetland. SF wetlands have been used to treat effluent from waste treatment lagoons, waste storage ponds, and milk houses as well as runoff from open feedlots. They have also been used to treat acid mine drainage and runoff from croplands and discharges from aquaculture facilities.

The effluent from most animal confinement facilities should be pretreated to reduce the total solids and nutrients before entering an SF wetland. The high concentrations of solids and other constituents of wastewater that typically emanate directly from the confinement facilities are unsuitable for most wetland plants without pretreatment. Pretreatment is especially important for reducing the high concentrations of solids and ammonia often associated with wastewater from livestock facilities.

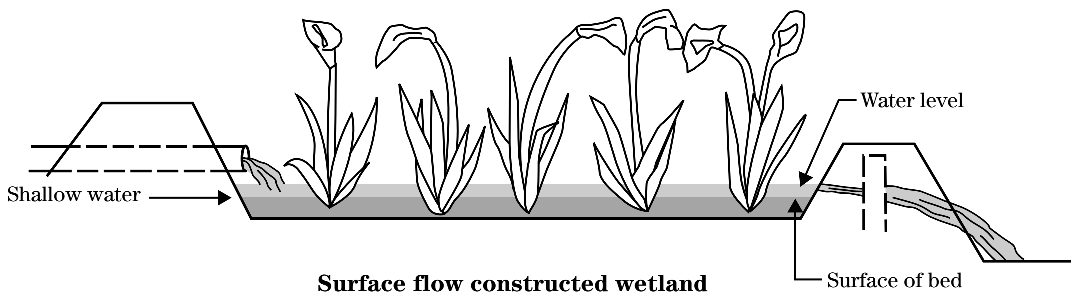
Data on the performance of SF constructed wetlands for treating wastewater from livestock facilities throughout the United States indicate that this type of wetland can be highly efficient in treating wastewater from confined animal feeding facilities. SF wetlands are relatively inexpensive when compared with SSF wetlands. In addition, SF wetlands are relatively easy to manage and maintain, especially when compared with floating aquatic plant systems. Surface flow wetlands function year-round, although some reduction in efficiency occurs in winter in colder climates. Even in the cold northern climate of Canada, SF wetlands are successfully treating animal waste (Knight et al. 1996).

(b) Subsurface flow wetlands

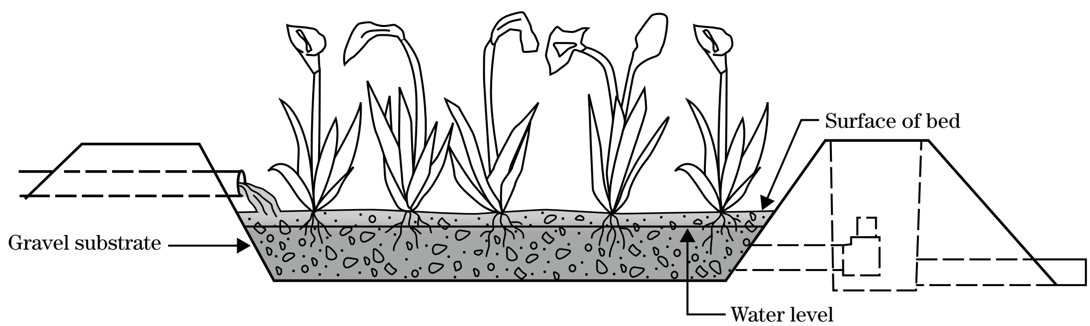
The SSF wetland contains a bed of gravel, rock, or soil media through which the wastewater flows. The bed is placed below ground level, and wastewater enters the bed at approximately mid-depth. Emergent, hydrophytic vegetation is planted at the surface of the wetland, often in a shallow layer of pine straw, wood chips, or other mulch. The roots of the plants extend into the saturated bed.

The water surface is maintained at an elevation just below the surface of the bed. The bottom slope, porosity of the medium, and daily average flows are critical engineering factors that must be considered to maintain the proper hydraulic gradient of the wastewater as it passes through the bed. Failure to account for these factors could result in a water level that drops below

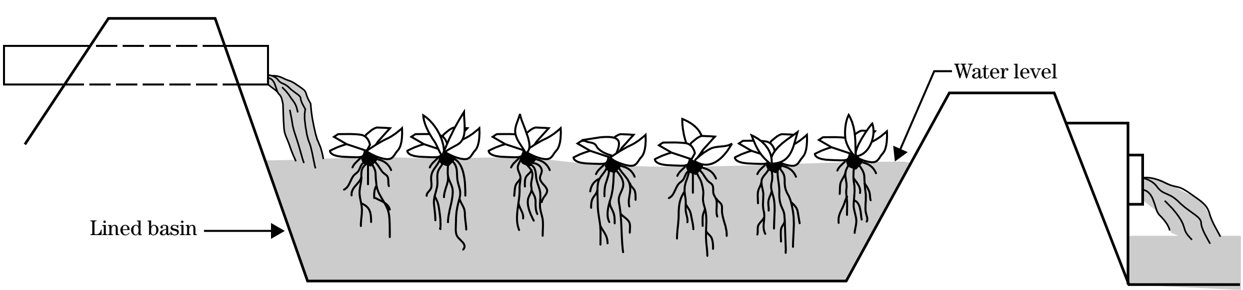
Figure 3–1 Types of constructed wetlands



Surface flow constructed wetland



Subsurface flow constructed wetland



Floating Aquatic Plant (FAP) system

the roots at the downstream end or a water level that rises, resulting in ponding of water on the surface.

In areas that have shallow groundwater or a seasonal high water table, groundwater can infiltrate into the bed and disrupt hydraulic conditions and treatment efficiency. Wastewater could also migrate from the subsurface wetland into the surrounding soil or groundwater. In this case hydraulics, treatment efficiencies, and plant survival could be altered. For these reasons, an impervious, fabricated liner should be installed in some SSF wetlands.

While SSF wetlands are successfully treating domestic wastewater, their use in treating wastewater from livestock facilities appears limited. The reasons for this are twofold. First, the porous bed can be easily plugged with solids. Even pretreated wastewater from most livestock facilities has high concentrations of solids. In addition, installing a large rock bed would be prohibitively expensive for most operations. The installation cost for a SSF system is expected to be at least five times the cost of a surface flow system (Kadlec and Knight 1996).

SSF wetlands could possibly be used to treat small flows that have a low-solids content, such as water used to clean milking equipment in a small dairy. For this use, a septic tank would need to be installed upstream of the wetland.

(c) Floating aquatic plant systems

The floating aquatic plant (FAP) system consists of a pond or series of ponds in which floating aquatic plants are grown. The ponds must be deep enough to prevent emergent plants from growing, but shallow enough to ensure adequate contact between the roots of the floating plants and the wastewater (depth range: 3 to 5 ft). In FAP systems plants grow profusely and extract a large amount of nutrients from the wastewater. Since harvesting is an essential management requirement, the number, size, arrangement of ponds, and method of harvesting must be taken into account during initial planning.

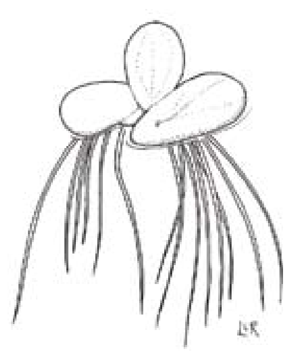
The most common floating plants used for wastewater treatment are water hyacinths (*Eichhornia crassipes*) (fig. 3–2) and duckweed (members of genera *Lemna*, *Spirodella*, *Wolffia*, and *Wolfiella*) (fig. 3–3). Both water hyacinths and duckweed grow rapidly and generally provide enough shade to prevent the growth of algae. By preventing the growth of algae, they prevent large diurnal swings in pH and dissolved oxygen concentrations associated with algal blooms.

Growth rate of water hyacinths is typically between 150 and 270 pounds per acre per day (Reddy and DeBusk 1987). Based on data from several municipal FAP systems, nitrogen (N) was removed at an average rate of 17 pounds N per acre per day when N loading ranged from 8 to 37 pounds per acre per day (Weber and Tchobanoglous 1985). Phosphorus (P) removal at municipal treatment plants generally does not exceed 30 to 50 percent, assuming an active harvesting program (Reed et al. 1995). Lower P removal is typical of unharvested FAP systems.

Figure 3–2 Water hyacinth

Source: Center for Aquatic and Invasive Plants, University of Forida

Figure 3–3 Duckweed



Source: Center for Aquatic and Invasive Plants, University of Forida

Duckweed grown in wastewater can double its area of coverage every 4 days at a temperature of 27 degrees Celsius (Reed et al. 1995). It is more tolerant of cold weather than hyacinths and can be grown for at least 6 months of the year in all areas of the country and throughout the entire year in Southern Coastal States and southern California. Water hyacinths, however, are not suitable for growth in the northern two-thirds of the country.

Duckweed has a low-fiber, high-protein, and high-mineral content, giving it excellent potential for use as livestock feed (table 3–1). Compared with water hyacinths, duckweed contains at least twice as much protein, fat, nitrogen, and phosphorus.

Water hyacinths and duckweed contain about 92 percent water. After harvesting, drying is normally required depending on the requirements of the final product. Plants can be dried in the sun or through mechanical means. Mixing the dried material with other ingredients and forming a pelleted feed has been employed, especially with duckweed. Composting is another viable alternative to convert these plants to a usable resource.

Research has shown that *Lemna gibba*, a species of duckweed, could survive well after several days in the supernatant for waste treatment lagoon for a swine operation with an initial total Kjeldahl nitrogen (TKN) concentration of 255 milligrams per liter and an ammonia concentration of 168 milligrams per liter. However, the improvement in ammonia removal was significant when the wastewater was diluted with clean water at a ratio of 1:1 (Cheng et al. 1998).

A comparison of SF and FAP systems for municipal wastewater indicates that FAP systems have lower reaction rates, higher construction and operating costs, more sensitivity to cold temperatures, and more susceptibility to plant pests and pathogens. The problem of plant pests and the need for a high level of pest management might be overcome by using a combination of plant species. If the FAP is considered for treating animal waste, an economic evaluation should be conducted during initial planning to determine if the end product, such as a high-value feed product, can offset the higher costs of installation, operation, and management.

As noted in this section, the SSF and FAP wetlands have certain disadvantages when used to treat animal waste. The SF wetlands have been used widely around the country and are currently the preferred method of treating animal waste. For this reason, the focus of attention in this chapter is on SF constructed wetlands.

Table 3–1 Composition of duckweed grown in wastewater [1/]

Composition	- - - Percent dry weight - - - range	average
Crude protein	32.7–44.7	38.7
Fat	3.0 –6.7	4.9
Fiber	7.3–13.5	9.4
Ash	12.0–20.3	15.0
Carbohydrate	—	35.0
TKN	4.59–7.15	5.91
Phosphorus-P	0.80–1.8	1.37

1/ Summarized by Hyde et al. (1984).

637.0302 Benefits of surface flow wetlands for animal waste treatment

The surface flow constructed wetland can provide important benefits for confined animal operations. These benefits relate to improved nutrient management, odor control, water quality improvement, wildlife enhancement, aesthetics, and economics.

(a) Nutrient reductions

In many cases, the decisionmaker wants to conserve nutrients in the waste since more nutrients can mean more value as fertilizer. However, some decisionmakers need to reduce nutrient loads either out of necessity, such as not having enough land for proper spreading, or because such reductions will provide some other advantage (see (b) Odor control and (c) Water quality improvement).

Nutrient reduction often becomes a necessity where land area for spreading is limited. In such cases the decisionmaker's options may be limited to:

- reducing the number of animals
- changing to a crop or cropping sequence that allows for higher nutrient use
- providing additional treatment of the wastewater

In each case, economic factors will also become important.

If the decisionmaker has a liquid waste system and elects to reduce nutrient content of the waste, the SF constructed wetland can be a viable option. Here, the wetland can be sized so that nutrients available after its treatment are consistent with the nutrient management plan for the application site.

Table 3–2 illustrates the value of SF wetlands in removing nutrients and organics from wastewater. The wetlands shown in the table differ in location, age, design, and type of wastewater; nevertheless, the data illustrate that SF constructed wetlands can provide significant reductions in nutrient loads.

(b) Odor control

Land application of some wastewater produces odors that are offensive to neighbors, even at some distance downwind. The anaerobic environment of SF wetlands can reduce these odors by reducing volatile solids concentrations. In addition, as wastewater passes through the wetland, the effluent typically has clearer color and less intense odor than the raw effluent from most waste treatment lagoons and waste storage ponds.

Where a constructed wetland is used to treat the effluent from a waste treatment lagoon, only the supernatant should be discharged to the wetland. Discharge of accumulated sludge from the lagoon to the wetland may kill the plants and create operational problems. Thus, sludge removal and its utilization apart from the wetland must be considered in planning.

Table 3–2 Annual percentage change in pollutant concentrations from two swine and three dairy facilities after treatment of waste treatment lagoon effluent in SF constructed wetlands

Constituent	Swine		Dairy		
	NC 1/	AL 2/	IN 3/	MS 4/	OR 5/
	% reduction				
NH_4-N	91	84	89	74	46
Org-N	90	83	62	—	47
Total P	34	46	84	53	45
PO_4-P	52	89	77	43	—
BOD_5	—	87	92	76	63
COD	55	80	—	64	52

1/ F.J. Humenik et al.
2/ T.A. McCaskey and T.C. Hannah
3/ R.P. Reaves and P.J. DuBowy
4/ C.M. Cooper and S. Testa, III
5/ J.A. Moore and S.F. Niswander
(Summarized in Constructed Wetlands for Animal Waste Treatment, Payne Engineering and CH2M-Hill (1997)

(c) Water quality improvement

Proper management of livestock waste is essential to protect surface and groundwater from contamination by nutrients, oxygen-depleting organics and ammonia, suspended and settleable solids, and microbial contaminants. However, wastewater from livestock facilities, even after the treatment in waste treatment lagoons or incidental treatment in waste storage ponds, can have high levels of pollutants that can degrade surface water or groundwater quality.

When wastewater from a waste treatment lagoon or storage pond is land applied, pollutants still have the potential to enter surface water because of over-application or through the movement of residual pollutants during storm runoff. This is especially true if buffer zones between application sites and nearby streams are too small.

To ensure maximum protection of surface water, the discharge of wetland effluent to surface water is not recommended although high treatment efficiencies can often be achieved. While reported treatment efficiencies vary, ammonia nitrogen and biochemical oxygen demand (BOD_5) have been reduced through wetland treatment by more than 75 percent over an extended period for some systems. Yet, despite these high levels of removal, the quality of wetland effluent may still not meet State discharge limits all year for all pollutants. Therefore, it is recommended that treated effluent be stored and land applied as opposed to discharging under a State-authorized permit.

The decisionmaker for a confined feeding facility who wishes to discharge treated effluent to a nearby stream must first obtain a National Pollution Discharge Elimination System (NPDES) permit from the State regulatory agency. Allowable discharge limits are based largely on the characteristics or waste assimilative capacity of the receiving stream and total maximum daily loads (TMDLs) allowed. Wastewater sampling and flow monitoring on a regular basis are typically required, which means that the treatment system must be reliable enough to meet discharge requirements throughout the year. A system permitted to discharge also typically requires a higher level of management and maintenance.

Although the quality of wetland effluent may not meet discharge requirements, it may be high enough to be used for other purposes than land application. Such uses may include flushing, cooling, and dust control.

(d) Wildlife enhancement

Constructed wetlands attract wildlife. Birds, mammals, amphibians, reptiles, and a variety of dragonflies and other insects frequent the area or make the wetland home. While any arrangement of cells enhances wildlife habitat, the layout can be modified to attract specific types of wildlife. In areas where biosecurity is a concern, consideration should be given to excluding migratory and other nonresident wildlife to minimize the potential for spread of disease to other operations.

An EPA publication (USEPA 1999) indicates that more than 1,400 species of wildlife have been identified for constructed and natural treatment wetlands. They include 700 species of invertebrates, 78 species of fish, 21 species of amphibians, 31 species of reptiles, 412 species of birds, and 40 species of mammals. More than 800 species were reported in constructed wetlands alone.

(e) Aesthetics

Wetlands have a unique beauty that in many regions of the country changes through the seasons. Even when planted with typical plantings, the character of the system changes as natural wild plants invade the system. While the choice of plants may be limited for the initial or upstream segments of the system because of the high concentrations of some pollutants, more colorful and a greater variety of plant species may be placed at downstream locations within the wetland system where wastewater quality improves.

(f) Economic benefits

Each operation must be evaluated individually to determine if the installation of a constructed wetland will provide an economic benefit. The benefit could come from reducing the land application area enough to install a solid set system versus a more labor-intensive traveling gun or center pivot system. Even if an economic analysis shows no net benefit from installing a constructed wetland, some decisionmakers might be willing to forgo some measure of annual benefit to reduce the amount of time spent in waste handling.

Some key factors that must be considered in an economic assessment include:

- Construction costs
- Value of nutrients lost through treatment by the wetland
- Equipment and labor costs to land apply wastewater
- Value of land used by constructed wetland
- Value of crop lost because of land taken out of production by the constructed wetland
- Cost of operation and maintenance

637.0303 Treatment process

Many physical, chemical, and biological mechanisms occur within treatment wetlands. Some are relatively simple and others complex, and some are not fully understood in terms of their contribution to the overall treatment process. The principal mechanisms are described in this section.

(a) Biochemical conversions

The wetland is alive with microorganisms that convert chemical compounds from one form to another. A large fraction of these organisms are attached to plant stems and litter and to sites throughout the soil and plant root complex. Others are free floating within the wastewater stream.

Since wastewater from most livestock facilities is generally low in or devoid of dissolved oxygen, the primary treatment organisms within the wetland are either obligate anaerobes (those requiring an oxygen-free environment) or various facultative types. The principal end products of anaerobic digestion are carbon dioxide (CO_2) and methane (CH_4); however, a variety of other minor gases are also generated in small quantities. Thus, the organic content of the wastewater as measured by 5-day biological oxygen demand (BOD_5), chemical oxygen demand (COD), and volatile solids (VS) can be greatly reduced through wetland treatment.

Anaerobic bacteria also convert organic nitrogen (Org-N) to the ammonia forms, NH_4+ and NH_3. Both forms, as expressed in the equilibrium equation $NH_4+ \leftrightarrow NH_3+ H+$, are considered to be ammonia nitrogen (Sawyer and McCarty 1967).

The conversion of ammonia to nitrite (NO_2) and then to nitrate (NO_3^-) requires an aerobic environment. Aerobic organisms are those requiring free-oxygen for respiration. Such an environment may be in microscopic zones around the roots and rhizomes of wetland plants and on substrates near the water surface. See details on nitrogen conversion within the root zone in 637.0304 Vegetation.

As the anaerobic, ammonia-laden wastewater is drawn into the root zone, any aerobic organisms present begin converting ammonia to soluble nitrate. Some of the NO_3^- is used by the plants, but much of it migrates back into the surrounding anaerobic region. Within this region, specific types of anaerobic bacteria denitrify the NO_3^-, converting it to atmospheric (N_2) gas, which is then liberated to the atmosphere. Figure 3–4 illustrates the pathways of nitrogen conversions.

Other compounds also go through biochemical conversions. Sulfur compounds can be converted to hydrogen sulfide under anaerobic conditions, and iron compounds can be reduced. Some compounds are lost to the atmosphere, and others are stored in the wetland sediment. Phosphorus does not have a gaseous state; therefore, organic P is converted through biological mechanisms to soluble P and then:

- lost in the wetland effluent
- extracted by the plants
- bound within the soil profile
- entrapped within the permanent peat-like bed that forms on the floor of the wetland (accretion)

Phosphorus is often removed in relatively high concentrations in many surface flow wetlands during initial startup. Much of this removal is due to the available cation exchange sites in the wetland soil. After 1 to 5 years (Kadlec and Knight 1995), P levels usually drop to stable long-term removal rate. In some conditions, the wetland may develop a temporary negative removal rate, releasing more P than it removed. Since clay soil has a high cation exchange capacity, a wetland constructed in clay soil will most likely provide a longer period of high P removal than a wetland with sandy soil. Typical removal rates for total P for animal waste constructed wetlands are in the range of 40 to 60 percent based on earlier NRCS design criteria (USDA NRCS 1991).

(b) Accretion

Accretion refers to the long-term buildup of a peat-like material on the floor of a SF wetland or on top of the filter bed of a SSF wetland. This material consists of settleable solids from the waste stream, the remnants of decayed plant litter, and microbial biomass. Recent additions of loose litter or thatch are not considered part of the accreted material. Accretion is the primary long-term removal process for phosphorus and metals after the soil has been saturated with these elements.

Design height of constructed wetland embankments must consider long-term accretion. The rate of buildup is typically less than 0.5 inch (1.3 cm) per year. When the depth allowance for accretion has been reached, the accumulated material should be removed to maintain the hydraulic effectiveness of the wetland cell. However, as has been stated, accretion is a long-term process. As an example, with an accretion rate of 0.5 inch per year, it would take 25 years to fill 1 foot.

(c) Settling/filtration

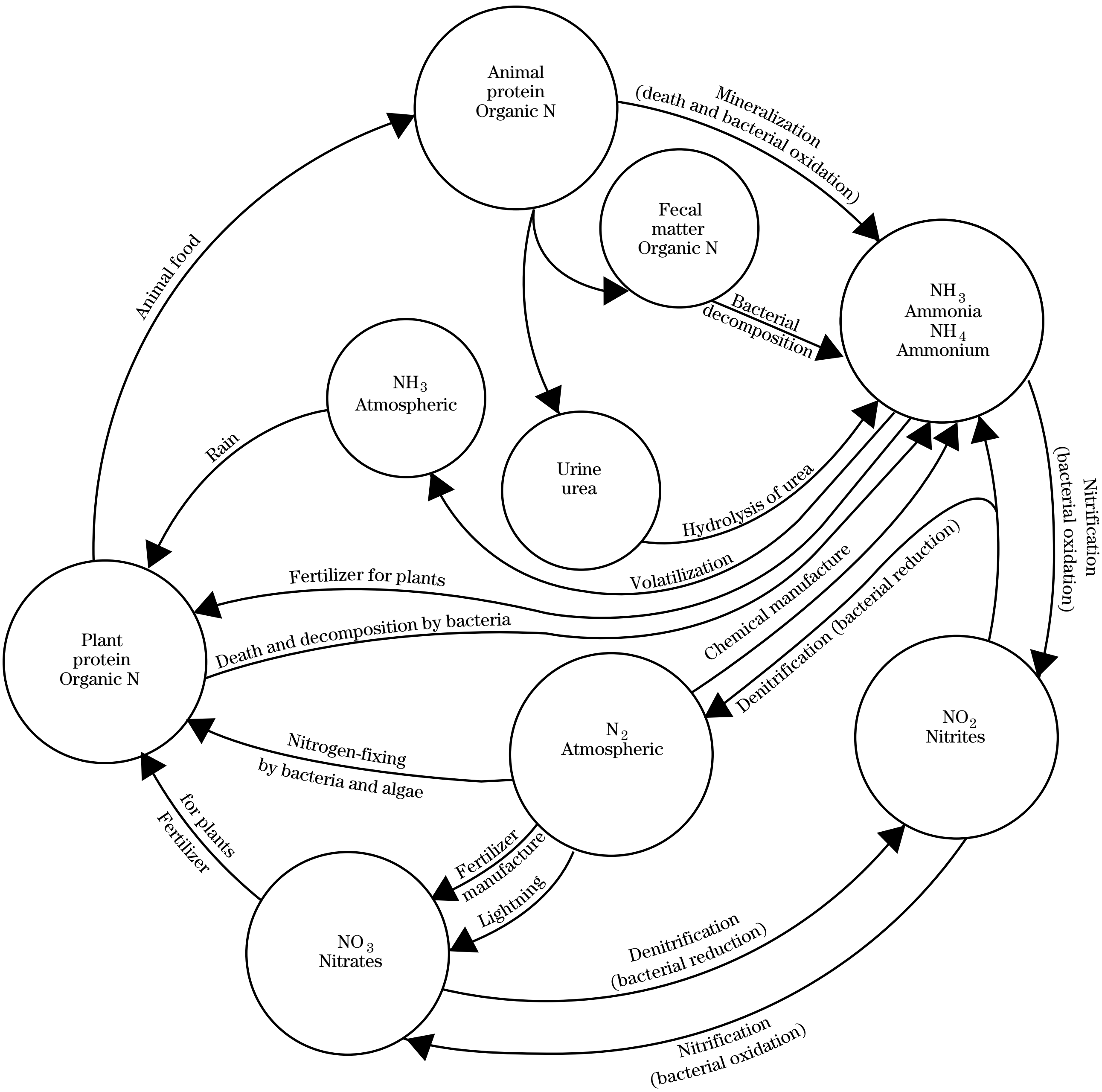
Solids entrained within the influent wastewater can settle to the bottom of the wetland and become part of the accreted material or can be filtered or entrapped by the plant stems and bottom litter. The floating material and settleable solids can be retained through this mechanism. Any settleable organic matter is eventually converted to more stable end products through biochemical conversions. Some of the material entering the wetland is relatively inert and, therefore, degrades slowly or becomes part of the permanently stored material in the accretion.

(d) Volatilization

The release of a compound from the surface of a liquid to the surrounding atmosphere is called volatilization. The rate of transfer from the liquid phase to the gaseous phase is governed by standard chemical equilibrium equations for the compounds in question. If the concentration of a compound in a gaseous phase is low or nonexistent, such as an extraneous compound would be in the Earth's atmosphere, the fraction contained in liquid phase continues to evaporate (converted to gaseous phase) until equilibrium is reached.

Ammonia is a compound that readily volatilizes and is one of great importance in animal waste management. Ammonia concentrations in anaerobic waste treatment lagoons typically represent 60 to 70 percent of the total nitrogen concentration, with the other 30 to 40 percent being in organic form. These same percentages apply to wastewater that enters most animal waste constructed wetlands.

Figure 3–4 Nitrogen cycle [1/]



1/ Source: U.S. Department of Agriculture, Natural Resources Conservation Service. 1992. Agricultural Waste Management Field Handbook.

While some nitrogen is lost through the denitrification process noted under NEH 637.0303(a), Biochemical conversions, additional N may be lost through the volatilization of ammonia. This is explained in part by the equilibrium equation for ammonia:

$$NH_4^+ + OH^- \Leftrightarrow NH_3 \bullet H_2O \Leftrightarrow NH_3\uparrow + H_2O$$

In this equation, NH_3 is the gaseous phase of ammonia. The expression $NH_3 \bullet H_2O$ represents the loose attachment of the un-ionized NH_3 molecule to the H_2O molecule. At the air/water interface, NH_3 can be volatilized; in which case the equation shifts to the right. If no equilibrium in NH_3 concentrations between air and water is reached, NH_3 is volatilized and the equation continues to shift toward more free $NH_3\uparrow$. The equation also illustrates the interrelationship between pH and the ammonia forms. Under highly alkaline conditions (high OH^-), more NH_3 becomes available in solution and more is available for volatilization.

In addition, the process is affected by temperature. Table 3–3 shows how temperature and pH affect the amount of un-ionized ammonia present in an aqueous solution.

Wastewater entering constructed wetlands from anaerobic waste treatment lagoons usually has pH in the range of 7.0 to 7.5. At 25 degrees Celsius, between 0.57 and 1.8 percent of the available ammonia is in the un-ionized form.

In waste treatment lagoons and constructed wetlands, the movement of wind across the surface of the wastewater enhances volatilization. Since the pH cannot be easily raised to enhance NH_3 volatilization, the process of ammonia removal in waste treatment lagoons and constructed wetlands is naturally slower than that in industrial and municipal systems where aeration is provided and pH is controlled. Nevertheless, as much as 90 percent of the original N entering an anaerobic waste treatment lagoon is lost, mostly through volatilization of ammonia. It is believed that a considerable amount of N is also lost in constructed treatment wetlands as a result of this process.

Table 3–3 Percent of un-ionized ammonia (NH_3) in aqueous solutions as related to pH and temperature

Temperature	- - - - - pH - - - - -					
(˚C)	6.0	6.5	7.0	7.5	8.0	8.5
15	0.0027	0.087	0.27	0.86	2.7	8
20	0.040	0.13	0.4	1.2	3.8	11
25	0.057	0.18	0.57	1.8	5.4	15
30	0.080	0.25	0.80	2.5	7.5	20

Research on ammonia losses from rice fields fertilized with ammonium indicates that loss rates were comparable to plant uptake for dense stands of macrophytes (Freney et al. 1985). In addition, Kadlec and Knight (1996) summarized various studies on the subject of ammonia volatilization and concluded that “volatilization typically has limited importance, except in specific cases where ammonia is present at concentrations greater than 20 mg/L.”

The influent ammonia concentration to constructed wetlands from livestock operations generally exceeds 20 milligrams per liter. For wastewater from swine operations that has been pretreated with a waste treatment lagoon, this influent ammonia concentration ranges from 200 to 300 milligrams per liter. Because of this, it would appear that ammonia volatilization is a significant pathway for the loss of N in this type of wetland. Further research on this issue is needed to quantify amounts lost under various climatic conditions.

(e) Interactions with soils

When wastewater enters the soil/plant-root matrix, various reactions can take place depending on the type and amount of clay, hydrous oxide, and organic matter present. In addition, the nature and type of chemical constituents in the solute as well as the pH and cation exchange capacity of the soil play important roles in the retention and conversion of pollutants.

Reactions within the soil complex include ion exchange, adsorption and precipitation, and complexation (Keeney and Wildung 1977). Cation exchange is the dominant exchange process in soils. In this process positively charged particles (cations) that are bound electrostatically to negatively charged (anionic) sites on soil colloids are exchanged with cations in the soil solution with little or no alteration of the solids. Since soil colloids have a net negative charge, many positively charged molecules in wastewater are readily bound within the soil profile.

Adsorption refers to the "adhesion of gas molecules, dissolved substances, or liquids to the surface of solids with which they come in contact," while precipitation denotes the formation of "a sparingly soluble solid phase" (Keeney and Wildung 1977). These two processes are often in competition, and determining which one dominates is often difficult.

Sorption, a term often used to describe adsorption and absorption, can involve weak atomic and molecular interactions (physical sorption) or stronger ionic-type bonds similar to those holding atoms in a molecule (chemisorption). The latter process is thought to be the primary mechanism for phosphate retention in acid (Seyers et al. 1973; Mattingly 1975).

A host of other interactions can occur within the soil. Metals, for instance, can react with soil in a variety of ways. In addition to the inorganic reactions that occur, metals may be subject to complexation, chelation, and biological transformations in organic soils.

The purpose of this section is not to explain the often complex interactions that can occur when wastewater enters the soil profile. This section simply illustrates that the soil is a vitally important and intriguing part of the treatment process within constructed wetlands.

(f) Evapotranspiration

Losses of water to the atmosphere from a wetland's water surface and soil (evaporation) and from the emergent part of the wetland plants (transpiration) are referred to collectively as evapotranspiration (ET). Since ET affects the overall water balance of a waste treatment system, it becomes an important factor in design. Factors that affect the rate of ET include incoming solar radiation, back radiation, cloud cover, time of year, latitude, wind velocity, amount of open water exposed to winds, and percent of water surface covered by litter or occupied by emergent plants, (Kadlec 1989). Differences in evaporation related to wetland plant type appear to be relatively unimportant (Linacre 1976).

Any attempt to predict ET losses based on energy balances could be a difficult task and could result in outcomes that may be no better than using empirical methods. With this in mind, the following guidelines are presented for estimating ET:

- Surface flow wetland ET over the growing season is nearly equivalent to 0.8 times Class A pan evaporation. Climate apparently has little effect on this relationship. Monthly and yearly Class A pan evaporation data can be obtained from data published by the U.S. National Oceanic and Atmospheric Administration (NOAA).
- Wetland ET and lake evaporation are approximately equal. This is simply a corollary of the paragraph above because Class A pan evaporation is roughly 1.4 times lake evaporation.
- For small wetlands, the ratios to pan and lake evaporation may not be adequate for predicting ET. While these ratios can be applied effectively to wetlands as small as 0.25 acre (0.1 ha), they may not be reliable for smaller wetlands because of the advective influences of the surrounding climate. In other words, ET is enhanced in small wetlands much as it is with potted plants.

The importance of ET can be seen in a simple calculation for a wetland with a 2-acre surface area. Assuming, based on climatic data, a lake evaporation of 36 inches (92 cm) per year, the annual ET would be about 261,360 cubic feet (7,396 m^3) per year, or nearly 2 million gallons. This yearly value is somewhat misleading because ET is not evenly distributed throughout the year; ET rates are typically much higher during the summer than during winter. Studies at the wetlands on the farm at the North Carolina Agricultural and Technical State University at Greensboro, North Carolina, show that it is common for evaporation rates to be 0.5 inches per day during hot dry summer periods. Even in northern climates, all wastewater applied to a treatment wetland can be lost through ET during a dry summer, as occurred twice in 10 years at a municipal treatment wetland in Michigan (Kadlec 1989). For this reason, consideration should be given to supplemental water that may be needed for the system.

Given the choice between the more detailed and rigorous method of determining ET and the use of empirical methods, the latter is recommended for estimating ET for animal waste treatment wetlands. Regardless of the method used, it should be noted that ET can result in a high degree of variability in hydrodynamics throughout any single growing season.

(g) Nutrient uptake

Wetland plants extract nitrogen, phosphorus, potassium, and various minor nutrients and metals from livestock wastewater. These constituents of wastewater may be used in the development of plant stems and leaves, or they may be stored for an extended period in the roots and rhizomes. Emergent plants used in SF and SSF wetlands remove nutrients during the growing season, but a large part of these nutrients are returned to the litter mass as plants die back in winter. A fraction of the decaying litter is released in the wetland effluent. However, some of the nutrients become part of the accretion, while others are permanently or semipermanently stored in the subsurface structure of the plants.

Harvesting plants in SF and SSF wetlands will remove only a minor amount of nutrients and other pollutants relative to the other processes noted above. Therefore, harvesting is not recommended. However, in FAP systems, nutrient removal by plants is significant simply because the plants and, hence, the nutrients are harvested and removed from the system.

637.0304 Vegetation

The U.S. Fish and Wildlife Service (USFWS) lists more than 6,700 plant species that are identified with wetlands. These include the obligate species that are exclusively in wetland habitats and facultative species that are in either wetland or upland areas. Only a fraction of this number is suitable for use in treatment wetlands, and fewer still would be suitable for use in treating high-strength wastewater, such as that from most confined livestock facilities. Nonetheless, a variety of wetland plant species has been used in the treatment of wastewater. Some have been purposefully introduced, and some are natural invaders. Guntenspergen et al. (1989) listed 17 emergent species, 4 submergent species, and 11 floating species that have been used in wetlands for treating municipal wastewater. Kadlec and Knight (1996) listed 37 families of vascular plants that have been used in water quality treatment. Be alert to using any plant species that may be considered invasive.

(a) Types of aquatic and wetland plants

The four major groups of macrophytic plants associated with wetlands in general are mosses, ferns, conifers, and flowering plants. However, the vast majority of plants used in wastewater treatment wetlands are flowering plants. Table 3–4 describes plants within the flowering plant group.

The emergent herbaceous plants are used extensively in municipal waste treatment systems throughout the world and are the most widely used plants in animal waste constructed wetlands. Although floating plants, such as duckweed, often fill open areas of surface flow wetlands, their contribution to the overall treatment process in this type system is incidental to that provided by the emergent herbaceous plants. Therefore, the focus in this publication is on the emergent herbaceous varieties.

Table 3–4 Flowering aquatic and wetland plants used in wastewater treatment

Growth habit	Description	Typical plants
Rooted plants		
Submerged	Main vegetative structure is completely underwater. Flowers or inflorescence generally extend above the water. Through photosynthesis, these plants produce volumes of dissolved oxygen, which facilitates aerobic decomposition. They may be shaded out where free floating plants are plentiful. Best adapted to deep water zones.	hydrilla (*Hydrilla*) egeria (*Egeria elodea*) frog's-bit (*Limnobium*) pondweed (*Potamogeton* spp.)
Floating (stems and leaves)	Roots extend into the bottom soil or may be attached at the shoreline. Plants may cover large areas in shallow water regimes. The shade they provide may affect water temperature. Such coverage may also reduce the population of algae and, thereby, reduce suspended solids concentrations in wetland effluent. Pennywort, attached at the shoreline, has spread profusely in open areas between emergent plants in some treatment wetlands.	water lily (*Nymphaea* spp.) spatterdock (*Nuphar* spp.) pondweed (*Potamogeton* spp.) pennywort (*Hydrocotyle* spp.)
Emergent herbaceous	Plants are rooted in the soil and have structures (stems and leaves) that emerge or stand upright above the water surface. As herbaceous plants, their structures are nonwoody, yet they stand erect above the water surface. **They are the primary plants used in constructed wetlands for treating animal waste.**	bulrush (*Scirpus* spp.) cattail (*Typha* spp.) common reed (*Phragmites*) duckpotato arrowhead (*Sagittaria* spp.) giant cutgrass (*Zizaniopsis* spp.) southern wild rice (*Zizania*) rush (*Juncus* spp.)
Emergent woody	Includes shrubs, trees, and woody vines. Distinguishing characteristics include bark, nonleafy vascular structure, decay-resistant tissues, and relatively long life. Used in municipal treatment wetlands. Their effectiveness in treating wastewater from confined livestock operations is uncertain.	cypress (*Taxodium* spp.) willow (*Salix* spp.) ash (*Fraxinus* spp.) gum (*Nyssa* spp.) birch (*Betula* spp.) alder (*Alnus* spp.)
Free-floating plants		
Free-floating to partly submerged	Plants may be rootless (*Wolffia* spp.) or have a root system that ranges from a single hair-like root (*Lemna* spp.) to roots that are several feet long (*Eichhornia* spp.). Roots, when present, are not attached to the soil, but extend into the water column. Plants reproduce rapidly, especially in a nutrient-rich environment. When used for wastewater treatment, harvesting is essential.	duckweed (*Lemna* spp.) water meal (*Wolffia* spp.) water hyacinth (*Eichhornia crassipes*)

(b) Emergent herbaceous plants

Emergent herbaceous plants (EHPs) are the dominant type vegetation used in wetland treatment systems, mainly because most treatment wetlands are surface-flow systems and the shallow water of these systems is ideal for this type vegetation. EHPs are also the dominant type vegetation in SSF wetlands. While floating plants (free-floating or attached) frequently enter SF wetlands through natural means, their presence is usually incidental.

Another factor favoring the use of emergent wetland plants is that they function in all latitudes of the United States, unlike some major floating plants. In addition, the best known and most versatile of the wetland plants (i.e., cattails, fig. 3–5, and bulrushes, fig. 3–6) are often available locally; thus, starter plants can sometimes be secured from farms or county and State highway departments when they are cleaning out road ditches.

Although these considerations are important, the two special reasons that make the emergent wetland plants important are the:

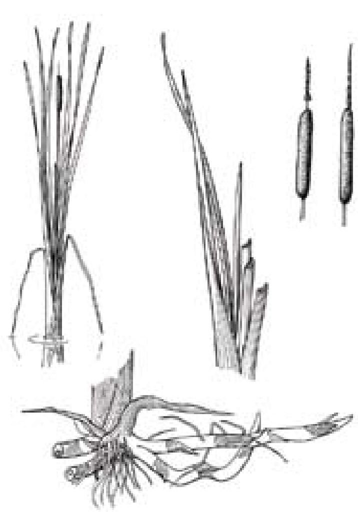
- special structural properties that allow these plants to survive in an otherwise hostile environment
- plants' special ability to facilitate the treatment process

The structural functionality of these plants and their role in the treatment process are presented here.

(1) Structural functionality

All plants require oxygen, nutrients, and water for various metabolic processes. When plant roots remain in saturated soil, the normal diffusion of gases to and from the plant roots is inhibited. Such gas transfers can still take place within the root zone if the water is oxygenated, but the process is much slower than in well aerated, but unsaturated soils. If the soils are saturated and also enriched with organic matter, anaerobic condition undoubtedly exists. In this case the roots are in competition with local microbial communities for any meager supplies of dissolved oxygen (DO) available; for most terrestrial plant species, the result is certain death.

Figure 3–5 Cattail



Source: Center for Aquatic and Invasive Plants, University of Invasive Plants, University of Florida

Figure 3–6 Bulrush

Source: Center for Aquatic and Invasive Plants, University of Invasive Plants, University of Florida

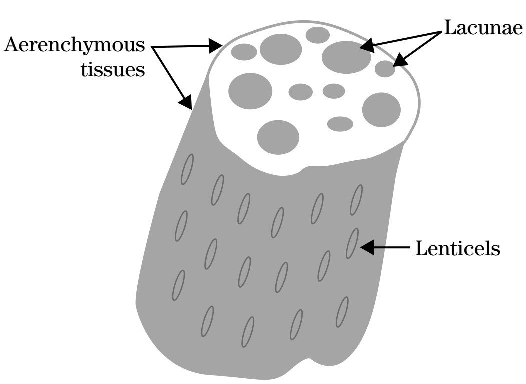
Many emergent wetland plants have adaptations that allow life to go on even in soil that is both continuously flooded and saturated with a high level of oxygen-demanding organic material, more specifically, wastewater. These adaptations ensure that oxygen is transported to the roots and rhizomes to satisfy the plant's respiratory demands.

Vascular wetland plants are equipped with aerenchyma or aerenchymous tissues containing lacunae, or a network of tiny hollow tubes that traverse the length of the plant allowing gases to move from the abovewater part of the plant to the roots and rhizomes, and vice versa. In addition, these plants have lenticels, or small openings along the plant stems that facilitate the flow of gases in and out (fig. 3–7). Lenticels may also be located on adventitious roots that develop from the stalk or stem of the plant within the water column. Other structural components include "knees" on cypress trees (an emergent woody plant) and buttresses, also on certain woody species.

The transfer of gases and in particular of oxygen from the abovewater part of the emergent herbaceous plants to the root zone can occur in two basic ways:

- passive molecular (gas-phase) diffusion
- bulk flow of air through internal gas spaces of the plant, resulting from internal pressurization (Brix 1993)

Figure 3–7 Features of an emergent-hydrophytic plant stem that allow movement of gases to and from the root zone



(2) Molecular diffusion

Brix (1993) describes molecular diffusion as follows:

> *Diffusion is the process by which matter is transported from one part of a system to another as the result of random molecular movement. The net movement of matter is from sites with high concentrations (or partial pressures) to sites with lower concentrations. The rate of diffusion of a gas depends on the medium in which the diffusion occurs, the molecular weight of the gas, and the temperature.*

Diffusion within the emergent herbaceous plants involves reverse gradients of O_2 and CO_2 partial pressures in the lacunae. Researchers have shown that in some plants a large decrease in O_2 concentration occurs between the aerial parts of the plants and the root zone, while gradients of CO_2 and CH_4 occur in the reverse direction (Brix 1993). The decrease in O_2 concentration was shown to range from 20.7 percent in the aerial stems to 3.6 percent in the lacunal air of the deepest-growing rhizomes, with the drop resulting from O_2 extracted for respiration (Brix 1993). In the same manner, CO_2 produced by respiration in the roots and rhizomes and CH_4 produced in the anoxic sediment diffuse along a reverse path with an increasing concentration gradient until these gases are expelled from the aerial part of the plant.

(3) Pressurized ventilation

The bulk flow of air into and through a plant can result from differences in temperature and water vapor pressure across porous partitions (i.e., plant leaves). Pressure is higher on the warm side and on the humid side of a partition, which can result in pressurization and airflow within the plant. In a study of water lilies, the external pressure was greatest in the youngest leaves, causing airflow into the leaves, down the petioles to the rhizomes, and back up to the older leaves where the air was vented back to the atmosphere. Internal pressurization and convective throughflow driven by gradients in temperature and water vapor pressure seem to be common attributes of a wide range of wetland plants, including species with cylindrical and linear leaves (*Typha*, *Schoenoplectus*, *Eleocharis*) (Brix 1993).

Another type of pressurization is called venturi-induced convection. Wind passing over the wetland flows at different velocities, with lower velocities

occurring near the water surface because of drag. At lower wind speeds, the pressure is greater. Thus, air is drawn into broken stems and culms closest to the water, circulated within the root system, and moved through the lacunae to points of lower pressure in the upper leaves and shoots. From there it is exhausted to the surrounding atmosphere (fig. 3–8).

The special structural features noted here do more than provide a means of respiration in the roots and rhizomes. In some cases an amount of O_2 exceeding the respiratory requirements of the roots and rhizomes occurs, resulting in O_2 exuding into the adjacent soil and creating microscopic aerated zones amid otherwise anaerobic conditions. The amount of O_2 leakage from diffusion has been reported to be in the range of 0.02 to 12 grams of O_2 per square meter per day (Brix and Schierup 1990; Brix 1993; and Armstrong et al. 1990) although higher values have been reported. Wetland plants that have a pressurized flowthrough mechanism for transporting oxygen to the roots and rhizomes have a greater potential for leakage and rhizosphere oxidation than those based on passive diffusion or pressurized mechanisms without flowthrough (Brix 1993).

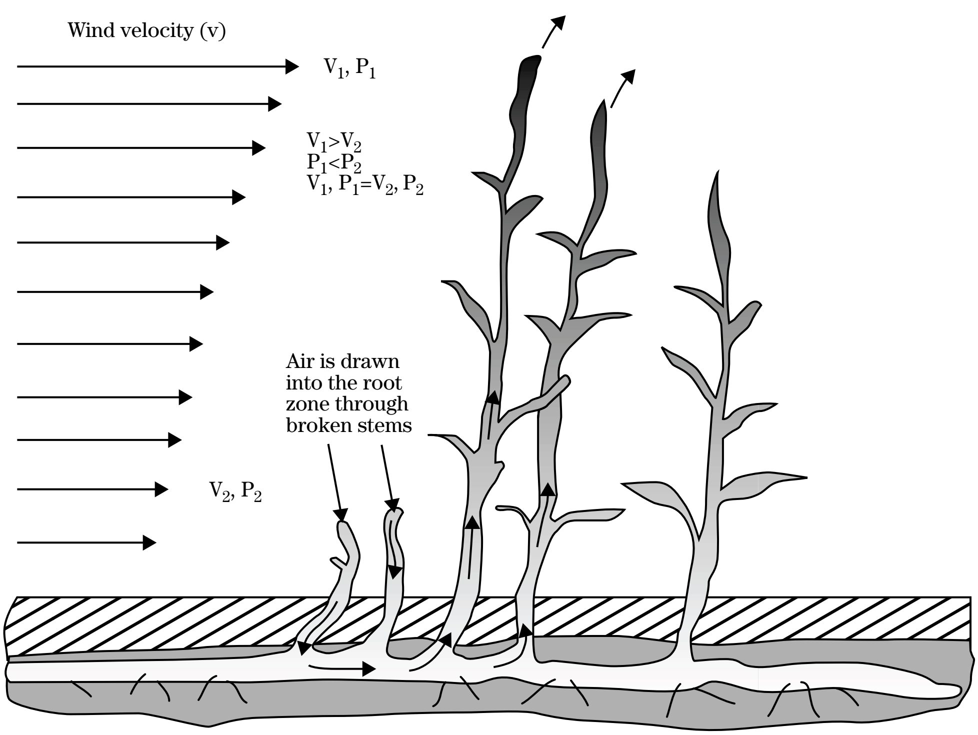
(4) Role of emergent macrophytes in the treatment process

The primary function of emergent herbaceous vegetation is not to remove nutrients and other pollutants through plant uptake; rather, it is to facilitate waste treatment. As facilitators, these plants play several roles in the treatment process:

- source of microbial substrate
- facilitator of nitrification/denitrification
- water and pollutant transporter
- users of nutrients
- filter
- source of shade
- source of new soils and sediment

Source of microbial substrate—Wetland plants provide solid surfaces or substrate on which bacteria and fungi grow. Fallen leaves, stems, flowers, and other residue from aging plants provide a large amount of surface area on which the treatment organisms thrive.

Figure 3–8 Illustration of venturi-induced convection throughflow as demonstrated in *Phragmites australis* (modified from Brix (1993)



The populations of organisms that inhabit the substrate are the driving force in the treatment process, causing pollutant concentrations to dramatically decrease as wastewater passes through the wetland. Reed et al. (1995) indicates that the microorganisms that populate the submerged plant stems, fallen leaves, roots, and rhizomes are responsible for much of the treatment within the wetland. Kadlec and Knight (1996) state the complex mixture of plant litter in various stages of decomposition and its highly productive biological communities are responsible for 90 percent of the overall treatment within surface flow wetlands. Thus, the principal function of the emergent herbaceous vegetation is to provide substrate for the microorganisms essential to the treatment process.

It becomes evident that the greater the surface area of the wetland, the greater amount of substrate present and, hence, the greater the effectiveness of the wetland. This assumes complete submergence of the litter and adequate contact time between wastewater and attached microorganisms.

Facilitator of nitrification/denitrification—An important function of the treatment wetland is to remove nitrogen. A large fraction of the nitrogen in animal waste treatment wetlands is lost through volatilization (NEH 637.0303). However, nitrogen can also be lost through a series of processes that lead to nitrate (NO_3) being converted to N_2 gas, which is liberated to the atmosphere. (Refer to figure 3–4, the nitrogen cycle, and table 3–5.)

Wastewater entering a surface flow wetland from a waste treatment lagoon or waste storage pond generally has little or no dissolved oxygen. Therefore, the nitrogen entering the wetland is either in the form of organic N or ammonia. The conversion from ammonia to nitrate is impossible unless the wastewater is somehow aerated, since aerobic bacteria are needed to make this conversion. Here is where the unique properties of the wetland plants become important, as explained in the conceptual model that follows.

As wastewater is drawn into the soil profile to satisfy the water requirements of the plants, it enters a zone that is basically devoid of oxygen (anaerobic), thus prohibiting the oxidation of ammonia to the nitrate form (NO_3). However, some O_2 seeps from the roots and rhizomes of the plants to form microscopic zones of aeration within the root complex (fig. 3–9). Within these aerobic zones, conditions are conducive for the growth of aerobic, nitrifying organisms that convert ammonia to NO_3. Some of this soluble form of nitrogen is used by the plants, but some migrates back into the surrounding anaerobic environment. Within the anaerobic zone, special types of bacteria called denitrifiers use NO_3 as a source of oxygen for respiration and, in the process, convert the NO_3 to N_2 gas, which then passes from the soil to the water column and then to the atmosphere.

Field-scale research to determine the actual amounts of O_2 exuded into the root zone and the extent to which nitrifying and denitrifying organisms make the conversions is still limited. Wetland systems are so complex in terms of types of plants, soils, and a host of other related factors that could influence oxygen transfer and biological activity, that the loss of N, however it occurs, is currently explained in terms of general rate constants based on influent and effluent sampling rather than on kinetics of individual microbial processes (Kadlec and Knight 1996).

Table 3–5 Processes involved in the conversion of organic and ammonia N to nitrogen gas

Process	**Conversion of N** from	**Conversion of N** to	**Condition required**
Ammonification	Organic N (Org-N)	Ammonia (NH_3 + NH_4)	Anaerobic or aerobic
Nitrification	Ammonia (NH_3 + NH_4)	Nitrite (NO_2) and Nitrate (NO_3)	Aerobic
Denitrification	Nitrate (NO_3)	Nitrite (NO_2) and N gas (N_2)	Anaerobic

Water and pollutant transporter—As plants draw water into the soil profile to satisfy their normal water requirements, they also bring various ionized pollutants into the matrix. As noted in NEH 637.0303, Treatment process, these potential pollutants can be inactivated through ion exchange, adsorption and precipitation, complexation, and oxidation and reduction. Without the plants serving as pumps to draw the wastewater into the soil, these reactions would not occur.

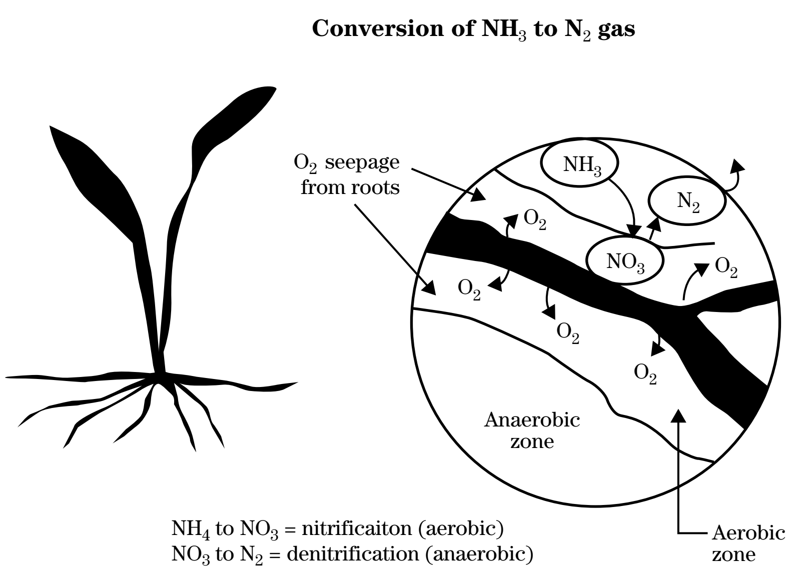
Users of nutrients—Plants use nitrogen, phosphorus, and the full range of minor nutrients. The amount taken up by the plants is generally small in relation to the full nutrient load in animal waste constructed wetlands. Nutrient utilization becomes especially important if plants are harvested. Otherwise, a high percentage of nutrients taken up by the plants are returned to the system as leaves and stems die and decay during senescence. A small percentage becomes stored in the accretion, some is stored within the roots and rhizomes, and some escapes the wetland in the effluent.

Filter—The matrix of plant stems and litter traps and retains a large fraction of the solids that enter the wetland. In addition, the plant/litter matrix slows the movement of water as it passes through the wetland, causing solids to settle. Thus, the plants facilitate the breakdown of organic matter by allowing more time for biochemical conversions to take place.

Source of shade—By shading the water, plants help regulate water temperature and reduce algal populations. The reduced concentration of algae prevents large daily swings in pH and dissolved oxygen concentrations. It also results in a lower concentration of suspended solids in the wetland effluent. This is especially important if the wetland has a permitted discharge. If the effluent is land applied using sprinkler irrigation equipment, the reduction of algae, especially the filamentous varieties, will reduce problems related to clogged pumps and nozzles.

Source of new soils and sediment—Over time, a layer of peat-like material gradually builds up on the floor of the wetland through a process called accretion. This material, sometimes referred to as new soil or deposited sediment, consists of plant residue, the remnants of the microbial organisms that were part of the treatment process, and nondegradable or slowly degradable solids trapped by the plants. The accretion rate is typically 0.08 to 0.39 inch per year for lightly loaded surface flow wetlands for municipal wastewater treatment (USEPA 1999). While TSS concentrations in pretreated influent to animal waste SF wetlands are typically higher than those for most municipal systems,

Figure 3–9 O_2 seepage and its interactions with N within the root zone



the total annual sediment load to municipal wetlands is expected to be higher because of a much greater annual influent volume. Although no data are available on long-term accretion rates for animal waste constructed wetlands, a rate of 0.5 inch per year appears ample based on a comparison of data from municipal and animal waste systems. Some of the phosphorus, nondegradable solids, and metals are permanently trapped in this layer. Accretion should be considered when designing embankment heights. It may be necessary to raise the embankments after a number of years to maintain the effectiveness or increase the effective life of the wetland.

637.0305 Planning for a constructed wetland—the systems approach

An agricultural waste management system (AWMS) may have numerous components. If treatment is needed, a constructed wetland could be integrated into the total system along with other structural, vegetative, and management components. Like other components, the wetland must be examined in light of other considerations, such as economics, odor control, wildlife enhancement, and regulations. Figure 3–10 illustrates the interrelationship of the key functional components of the AWMS and shows, through a Venn diagram, how the functional components are enveloped by other considerations.

All three of the key functional components are part of a constructed wetland. The embankments and water level controls are structural components. The wetland plants and grass on the embankments are vegetative components, while all aspects of controlling water levels and maintaining vegetation and embankments are management considerations. In the Venn diagram, note the overlap between components. The wetland is only one component of the total system, and interaction of all components should be addressed in an overall AWMS plan. Water management, nutrient management, and other aspects of the system are subsets of the AWMS plan. For a more detailed description of agricultural waste management systems planning, see the NRCS Agricultural Waste Management Field Handbook (USDA 1992).

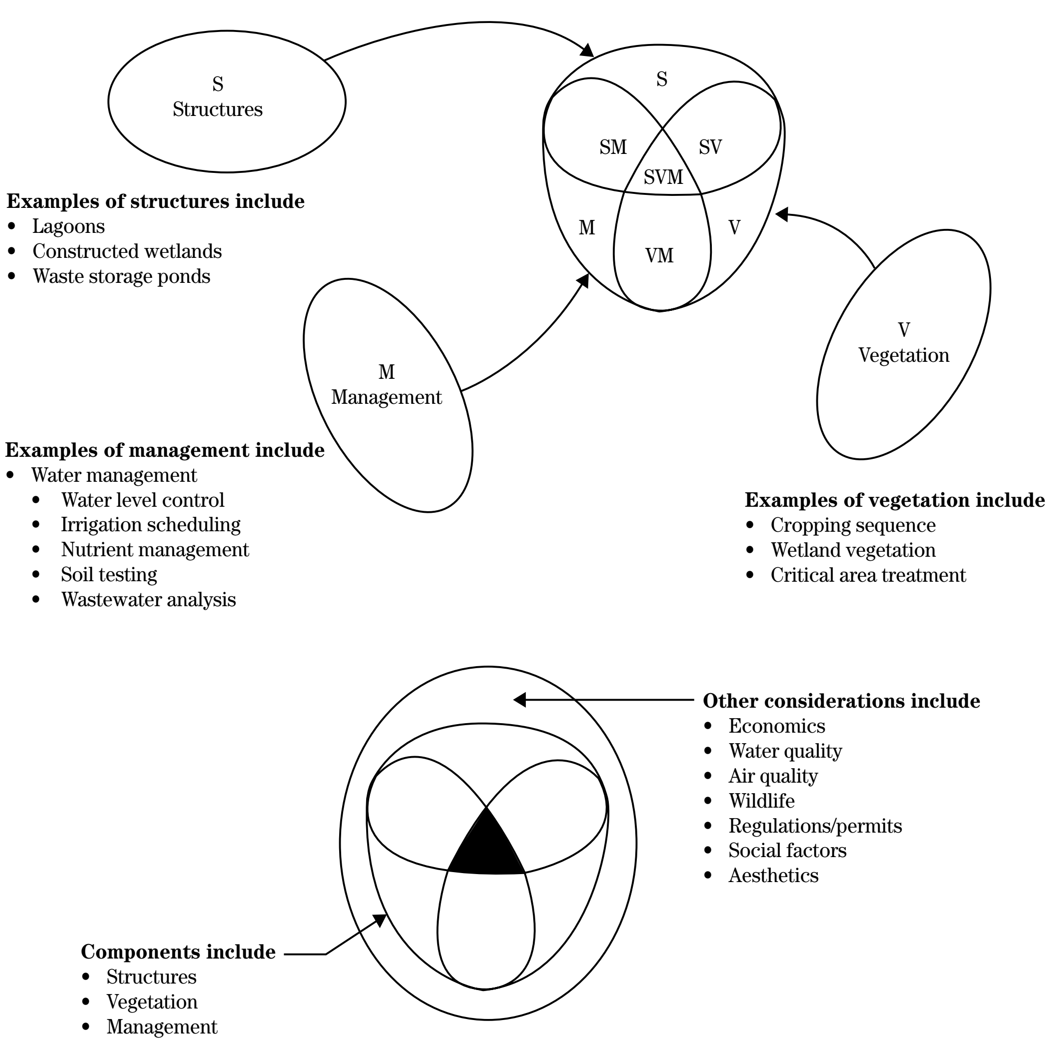
Although the constructed wetland is part of a system, some planning factors specific to the wetland component must be addressed. Listed below are some key factors to consider, with a brief explanation of each. An interdisciplinary team, consisting of engineers, soil scientists, geologists, agronomists, biologists, and others, must be involved in the site-specific details and methods for integrating this component into the system.

(a) Pretreatment

Wastewater from all confined animal feeding operations must be treated before it is discharged to a constructed wetland. Raw, untreated effluent typically contains concentrations of solids, organic matter, and nutrients high enough to kill most wetland plants.

Waste treatment lagoons, waste storage ponds, and settling basins have been used for pretreatment, but the selection depends on the characteristics of the raw wastewater and the desired level of treatment. For instance, an underground tank has been used to collect runoff from an open lot at a small dairy before the effluent is discharged to a wetland, and the results were satisfactory. However, solids must be removed regularly in such situations, and the use of a septic tank or a small settling basin is impractical in most situations where a large number of animals are involved or where the solids cannot be removed on a regular basis.

Figure 3–10 Venn diagram of agricultural waste management system



(b) Wastewater characterization

The characteristics of the wastewater being discharged to a wetland must be determined in advance to see first if the pollutant load will be too great for the wetland and then for the purpose of designing the wetland. The wastewater characterization should address both the pollutant load and the volume produced. Laboratory testing should be used to determined the pollutant loads, and measurements made to determine volumes produced. Estimates for pollutant load and volume produced are necessary for new systems. A further explanation of the influent characterization process follows.

(1) Pollutant load

For purposes of design, the wastewater pollutant load can be characterized by estimating techniques or by analyzing the supernatant of the pretreatment facility. Estimates must be used if the system is new and the pretreatment facility has not yet been installed or is not fully operational. However, for design of a constructed wetland that will be added to an already operational waste management system, it is always best to use laboratory test data for the actual wastewater proposed to be treated by the wetland.

If a waste treatment lagoon or other pretreatment facility is in place and nearly full, a representative sample of the supernatant should be collected and analyzed for total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3 + NH_4 + – N), total phosphorus (TP), total suspended solids (TSS), pH, and BOD_5. Ideally, samples should be collected during several months to reflect both warm-season and cool-season conditions. Samples must represent the conditions when the pretreatment component will discharge to the wetland.

Estimates of wastewater strength can be made using tables and other information in the NRCS Agricultural Waste Management Field Handbook or in other professional engineering publications. The estimates should only include the supernatant or that part of the wastewater stream that will be discharged to the constructed wetland. For instance, data tables may indicate that the nitrogen load can be reduced by 80 percent in an anaerobic waste treatment lagoon through volatilization. However, half of the remaining 20 percent may be retained in the settled sludge. In other words, only about 10 percent of the original N may be available for discharge to the wetland through the supernatant.

(2) Volume produced

A reasonable degree of accuracy is needed in determining annual and seasonal wastewater flows. Information about volumes is needed not only for designing the wetland, but also for planning effluent storage and land application requirements. The total volume of wastewater produced and entering the wetland includes input from such sources as manure, which displaces water in the pretreatment facility, flush-water, and rainwater. (For further information, see NEH 637.0306(j), Design of surface flow wetlands, Water budget.)

(c) Site evaluation

An onsite evaluation is essential to determine if any physical restrictions will prevent installation of the wetland or require modifications in design, layout, and operation. Soil maps, contour maps, aerial photos, and other “office” tools should be used in the evaluation. Some of the factors that should be considered during the onsite evaluation are noted in this section.

(1) Soils

Soil borings or backhoe pits should be dug at several locations within the boundaries of the proposed wetland site. Borings or pits should extend to a depth of at least 2 feet below the proposed constructed bottom elevation of the wetland to determine if permeable seams, shallow bedrock, or high water table are present and to evaluate soil permeability.

The hydraulic head (h) is relatively small for constructed wetlands (usually less than 18 in); therefore, the potential for seepage is expected to be minimal, assuming a moderately clayey soil is available or a well-compacted liner is installed. However, a detailed evaluation of potential seepage should be conducted at questionable sites (sandy soils, underlying limestone rock). To reduce the potential for seepage, soils should contain a relatively high concentration of clayey material. Soil classified as clay, sandy clay, sandy clay loam, or clay loam is suitable for use in a wetland. Clayey soil may inhibit the growth of some wetlands vegetation, but traditional plants, such as cattails, bulrushes, and reeds, have adapted to this type soil.

If the soil in the top 12 to 15 inches (30.5 to 38 cm) is highly permeable (sandy) or a sand or gravel seam is located within this layer, the surface material should

be removed and a compacted clay or fabricated liner installed. Once the liner is installed, the original material can be replaced. Specific guidance for determining when a liner is needed and details for its design are in the NRCS Agricultural Waste Management Field Handbook, appendix 10D.

Since the rooting depth of most surface flow wetland plants is typically less than 12 inches (30 cm) and about 80 percent of the root mass for most emergent plants is in the top 6 inches (15 cm) of soil, the top of the liner should be 12 to 15 inches (30 to 38 cm) below the intended surface of the wetland. In other words the medium for plant growth that overlies the liner should be at least 12 inches thick.

A soils investigation also determines the depth to and type of bedrock. A liner should be considered if bedrock consists of easily solubilized limestone or if fractured sandstone is within 3 feet of the proposed wetland bottom. The characteristics of the soil and soil depth should be carefully evaluated in this case.

(2) Effluent storage

Wetland effluent must be stored unless permits have been obtained to allow for its discharge to surface water. The storage facility, at a minimum, must be large enough to contain the effluent volume from the wetland between land application events or other uses. The storage facility, of course, must also be designed to contain runoff water, direct precipitation on its surface, and the input from other sources. An alternative to this type storage is returning the effluent to the upstream pretreatment facility.

A water budget is needed to determine the required capacity of the storage facility, whether it is located in a downstream pond or in the pretreatment facility. See NEH 637.0305(d), Hydrologic and climatologic data, and NEH 637.0306(j), Water budget.

(3) Topography

The lay of the land impacts the size and layout of the wetland system and the construction costs. All wetland cells should have a level bottom side-to-side and a flat or nearly level bottom lengthwise. If the land has considerable slope, several cells may need to be installed in series to maintain a relatively constant water depth. A new embankment is needed with each new cell; thus, more area is needed for the system.

The wetland should fit within the existing topography in such a way that, wherever possible, earthwork cuts and fills can be balanced during construction. A slight slope in the direction of the outlet end of each cell allows for complete drainage of the cell for maintenance. However, the same purpose can be achieved by installing a deep zone at the end of the cell that can be used as a sump for pumping and draining the cell. For further information, see NEH 637.0306(f)(1), Wetland configuration, Bottom gradient/maximum length.

(4) Land area

The amount of land used for the wetland and downstream storage pond depends on the level of treatment desired and the topography. In some cases the amount of land needed for the wetland component includes more dry land for embankments than actual wet land or surface water area. The economic consequences of replacing productive land with a treatment wetland should be evaluated in light of production lost as well as benefits gained. In addition, the installation of the constructed wetland will mean a reduction in nutrient content and, therefore, less land needed for spreading waste at the final application site.

(5) Surface water

The proximity of the wetland to the nearest stream or waterbody should be noted in the AWMS plan.

(6) Groundwater

The depth to groundwater and the distance to and depth of nearby wells must be established. The placement of the wetland must conform to State regulatory requirements concerning setback distances from wells.

If the wetland location satisfies the separation distance from a well, but only marginally so, well water samples should be collected prior to construction and evaluated for fecal coliform and fecal streptococcus bacteria (or other bacteria that may be specified by the State regulatory office), nitrates (NO_3–N), and ammonia nitrogen (NH_3 + NH_4–N). Without preconstruction sampling and testing, it cannot be established whether the wells were contaminated before operation of the constructed wetland.

If shallow depth to groundwater is noted, installation of at least one monitoring well downslope of the wetland or in an area selected by a qualified geologist is suggested. State regulatory officials should be con-

sulted if a seasonal high water table will be in close proximity to the bottom of the wetland.

(7) Flood plains

Flood plains are lowland areas that are adjacent to rivers, lakes, and wetlands and are covered by water during a flood. The ability of the flood plain to carry and store floodwater should be preserved and respected to protect human life and property from flood damage. Preservation of an active flood plain with adequate capacity is also important in maintenance of stream/riparian ecological function. For this reason constructed wetlands should be placed outside the flood plain if possible. Another reason for placing constructed wetlands outside the flood plains is so they will not be subject to inundation and damage.

Flood plains are delineated by the frequency that a flood of a given magnitude has the probability of occurring, such as the 1-year, 25-year, 50-year, and 100-year flood events. If site conditions require location of constructed wetland within a flood plain, it should be protected from inundation or damage from at least the 25-year storm event. Of course, if planning and design for a larger flood event is required by laws, rules, and regulations, such an event should be the one used. Important questions to consider if a constructed wetland is being planned within a flood plain are:

- Will the installation of the wetland cause upstream or cross-stream flooding during a flood event?
- How much will it cost to protect the wetland and downstream storage pond from being overtopped by the design flood event?

The State regulatory agency and, possibly, the U.S. Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA) may need to be consulted when considering placement of the wetland and storage pond within the flood plain.

(8) Fencing

Fencing around the wetland may be required by State regulations, or it may be needed because grazing animals could have access to the area. Grazing animals (cattle, goats, sheep) can seriously damage wetland plants and the embankments. Fencing or other preventive measures may be used to exclude burrowing animals, such as nutria and muskrats, both of which have been a problem in constructed wetlands. While there are cost benefits to not including fencing, there are also advantages to having it.

(9) Jurisdictional wetlands

The constructed wetland should not be planned for an area defined as a jurisdictional wetland. A technical specialist trained in how to make wetland determinations should evaluate the site if there is any doubt about this issue.

(10) Sociological factors

If the livestock facility and other waste management components are already in place, the addition of a treatment wetland should be of little concern to neighbors as compared with other more noticeable components. Since odors are often the major issue with livestock facilities, the addition of the wetland should be promoted for its benefits to air quality. (See NEH 637.0302, Benefits of surface flow wetlands for animal waste treatment.) Nevertheless, the location of the wetland can still be a concern simply because of its proximity to property lines or because of the types of wildlife that might be attracted to these systems.

Although serious mosquito problems have not been reported at most animal waste constructed wetlands, the possibility for problems exists. Mosquitofish may be able to survive in some wetlands for treating livestock wastewater and provide a natural control of mosquito breeding. If mosquito problems occur, controls may include scheduled manipulation of water levels or the application of a bacterial insecticide, such as Bacillus sphaericus.

(d) Hydrologic and climatologic data

Data on precipitation, pan evaporation, and temperature are needed for design of the wetland and the downstream storage pond. The data must be gathered during the planning process. Rainfall and evaporation data, along with other inputs, are used to determine:

- annual flow through the wetland, which is used in the Field Test Method to size the wetland (for further information, see NEH 637.0306(d), Field test method)
- hydraulic retention time in the wetland
- effluent volumes and, hence, the size of the effluent storage facilities, whether located downstream or upstream

- overall water budget, which is important in planning the land application component of the system

All sources of direct precipitation and runoff must be considered in determining the annual flow rate for the design equation. This may include direct rainfall on the waste treatment lagoon and wetland as well as runoff from embankments, roofs, open lots, and other areas draining into the system. This information is combined with data on manure and flushwater volumes to determine monthly and annual flows into the wetland. It is also key to designing for dormant-season storage and establishing land application requirements.

The annual ET within a wetland is presumed to be equivalent to lake evaporation. Lake evaporation is generally considered to be about 80 percent of pan evaporation. ET losses in a constructed wetland can exceed a livestock facility's wastewater production during the warm season of the year. Where this will occur, a continuous flow through the wetland must be assured by managing the upstream treatment facility or by introducing water from another source to prevent the wetland from drying out.

Temperature data are used in equations to size the wetland. If the wetland is being designed for a discharge, average monthly ambient temperature for the coldest month should be used for water temperature.

A wetland system can be designed for year-round operation even where ice will cover the wetland throughout most of the winter. In these cases, the anticipated thickness of the ice and expected maximum depth of wastewater flow are considered along with other factors. However, this type operation is not recommended for animal waste constructed wetlands.

If wastewater is stored during the winter months and if a discharge is planned, the average monthly temperature for the coldest month during the discharge period should be used for design. However, if the wastewater is released to the wetland only during the warmer months and if the wetland is used to reduce nutrients to a specific level required by the nutrient management plan for the land application area, then the average temperature over all months of the warm season should be used in design.

No hard and fast recommendations are provided in the literature for hydraulic detention time. However, it is obvious that some fraction of time is necessary for biological processes to reduce concentrations of most pollutants. Reed et al. (1995) have suggested that a hydraulic retention time of 6 to 8 days is necessary to provide for oxygen transfer in fully developed root zones to affect desired levels of nitrification. This and other limited information for other pollutants suggest that a minimum detention time should be 6 days. Longer detention times provide more complete treatment. A 14-day detention time may be a good target.

(e) Regulatory requirements

Planning must consider applicable regulations governing the installation of constructed wetlands. They would include regulations pertaining to jurisdictional wetlands, odors, and setback distances from property lines, wells, neighboring houses, streams, roads, and other areas of concern.

(f) Impacts on wildlife

Some concern may exist regarding the potential for transmission of diseases and the impact of the bioaccumulation of toxic substances to migratory animals. The USEPA (USEPA 1999) indicates that "quantitative data of direct or indirect toxic effects to wildlife in treatment wetlands are generally lacking." However, the document acknowledges that some potential for detrimental effects to wildlife may exist because of the chemical forms of some toxic substances. However, they also indicate that "wetland environments are typically dominated by plant and animal species that are hardier and less sensitive to pollutants than more sensitive species that may occur in other surface water."

Given the wide use of municipal and industrial treatment wetlands throughout the world and the paucity of data reflecting damage to wildlife, it appears that treatment wetlands present a low risk for transmission of disease or for bioaccumulation in any migratory animals, especially those that may be associated with animal waste. Planners might also take into account the fact that migratory animals have traditionally had access to other types of animal waste practices (open feedlots, treatment lagoons), and the installation of a constructed wetland would probably provide no greater danger than existing systems.

(g) Operation, maintenance, and monitoring

The decisionmaker needs to keep certain records on operation and maintenance as an aid to ensuring that the system continues to function as required. At a minimum, the inlet and outlet pipes should be checked daily because clogging by various types of debris can be a problem. A limited checklist schedule follows:

Operation, Maintenance, and Monitoring Checklist

Suggested time	Check	Action
Daily	Inlet and outlet pipes, water level (Water levels may be a clue to short-circuiting caused by burrowing animals.)	Adjust as needed
Monthly	Embankments, emergency bypasses, and fences (Ensure that no damage has occurred from animals.)	Record dates that embankments were mowed.
Quarterly	Wastewater sampling at inlets and outlets. Check for nutrient concentrations (TKN, NH_3+NH_4-N, NO_3-N, and TP) using a composite sample approach.	When samples are collected for analysis, measure flow rates at inlets and outlets using a bucket and stopwatch.
As desired	Identify wildlife.	Record wildlife identified, including birds, amphibians, reptiles, and insects (a good family or youth group project).
When needed	Recordkeeping required as part of the comprehensive nutrient management plan.	

637.0306 Design of surface flow wetlands

(a) Background

The design of wetlands for animal waste treatment, as presented here, uses best available technology based on data from a number of animal waste treatment wetlands throughout North America and on proven technology in the field of municipal waste treatment wetlands. As with the design of other biological treatment processes, the design of treatment wetlands is not an exact science because biological processes are often subject to influences that are highly unpredictable and variable, such as climatic changes. Nevertheless, the state of the art has advanced considerably, and wetlands can be sized and treatment performance predicted within a fairly high degree of accuracy, given the fact that anomalies occur from time to time.

In the early 1990s, the Agricultural Stabilization and Conservation Service, now the Farm Service Agency, initiated a trial cost-share program for constructed wetlands to treat wastewater from livestock and aquaculture facilities. Technical guidance was needed to support this program. Only a few animal waste constructed wetlands were in place at that time so the amount of data on treatment efficiencies on which to base this guidance was limited. Therefore, to meet the need for technical guidance, the NRCS National Headquarters formed an interdisciplinary team to review available information on constructed wetlands and develop requirements for planning, design, construction, operation and maintenance, and monitoring of constructed wetlands. The document resulting from this effort, *Constructed Wetlands for Agricultural Wastewater Treatment Technical Requirements*, was published August 9, 1991. This chapter and Practice Standard 656, Constructed Wetland, replace these technical requirements.

The technical requirements were issued with a caution: "Significant parts of the technology are not well understood. Consequently, caution should be exercised in approving constructed wetlands outside the ASCS cost sharing program." They further indicate that the performance of constructed wetlands developed under the program should be monitored with assistance of university personnel and State natural resource and regulatory agencies.

Two procedures were presented: presumptive method and field test method. The *presumptive method* is based on estimates or presumptions about certain pollutants entering the wetland. With this approach an estimate is made of the amount of BOD_5 or nitrogen produced by the animals and the amount lost through treatment before entering the wetland. The presumed amount of influent BOD_5 or N was then applied to a given areal loading rate (i.e., 65 lb BOD_5/acre/d) to determine wetland size. This methodology was taken from design information developed by TVA and used in 1989 to design a treatment wetland for a swine research facility at Auburn University's Sand Mountain Experiment Station in Alabama. The design was based on a fixed areal loading rate that is intended to provide treatment to the level required for municipal constructed wetland effluent to be discharged meeting the standard discharge limit of 30 milligrams per liter of BOD_5 or less. Since constructed wetlands for animal waste treatment are generally not designed for discharge, use of a design loading rate meant to provide treatment to a level to allow discharge may be treatment in excess of what is actually needed.

The *field test method* was based on equations developed by Reed et al. (1988). This approach was typically applied to municipal treatment wetlands. It assumes that samples of wastewater in the pretreatment facility can be analyzed before designing the wetland. Information on a given influent and expected effluent BOD_5 or total nitrogen (TN) concentration, average daily flow rate, temperature data, decay rate constants for given pollutants, average depth of the wetland, and an effective wetland volume factor would be entered into an equation to determine the surface area. The effective wetland volume factor, sometimes called porosity, is the amount of wetland water volume not occupied by plants and expressed as a decimal.

The methods presented in the NRCS technical requirement assumed that the effluent concentration would not exceed typically allowed discharge limits for BOD_5, ammonia, and total suspended solids. Establishment of these limits for designing the wetland was not intended to encourage discharges, but was, rather, to serve as a benchmark and to promote consistency in design throughout the country. Moreover, the NRCS guidelines stated that effluent could be discharged

only if appropriate Federal, State, and local permit requirements were satisfied. Otherwise, the guidelines required that the wetland effluent be collected in a storage facility and held until it could be land applied or recycled.

After several years of evaluation and after the national database on animal waste constructed wetlands was compiled (CH2M Hill and Payne Engineering 1997), it became apparent that the original design methods were in need of modification. It was also clear that wetlands could be sized for nutrient management or odor control (see NEH 637.0302, Benefits of surface flow wetlands) rather than sizing to satisfy regulatory discharge requirements (Payne and Knight 1997, 1998).

As a result of these findings, a *modified presumptive method* and a *new field test method* were developed. These methods are based on new equations advanced in the larger field of wetland design (Kadlec and Knight 1996) and on data from many animal waste constructed wetlands (CH2M Hill and Payne Engineering 1997; Payne and Knight 1998). The revision of these approaches to design is presented here.

The primary goal of both approaches is nutrient management, as described in NEH 637.0302, Benefits of surface flow wetlands for animal waste treatment. In other words, the wetland is sized so that the total annual nutrient load (TN or TP) in the wetland effluent matches the annual needs of the crops at the final land application site. The land area available for spreading wastewater is assumed to be the limiting factor.

The earlier presumptive model (USDA 1991) was a one-size-fits-all approach with the goal being to reduce pollutant levels to those allowed for discharge (30 mg/L BOD_5). No provision was made for adjusting the outflow concentrations to some value other than those fixed by NPDES permit requirements. The previous field test model could be used for that purpose, but procedures for doing so were not discussed.

The newer models use an areal loading technique to determine wetland size versus volumetric loading. The earlier presumptive method used this approach, but the earlier field test method was based only on volumetric loading.

Areal loading is based on the premise that a large fraction of the biological treatment within the wetland is associated with microorganisms attached to the surfaces of submerged litter, fallen leaves, soil, and plant stems. As noted in NEH 637.0304, Vegetation, as much as 90 percent of the treatment may be associated with vegetative surface area. Thus, raising the water level to increase detention time does not produce a proportional increase in treatment performance. This is because the additional substrate added from the newly submerged plant stems is small in comparison to the amount of substrate already submerged.

Therefore, it has been concluded that surface area of the wetland is paramount to effective treatment as opposed to water depth. Consequently, surface area of the wetland is determined by theoretically applying a given amount of a particular pollutant over some unit of surface area per unit of time. Units of loading are expressed in such terms as pounds per acre per day. It should be understood, of course, that the use of such units does not imply that influent wastewater is sprayed uniformly over the entire surface area of the wetland; rather, it is simply an expression needed to quantify the relationship between rate applied and surface area of the treatment unit.

(b) Wastewater storage

Unlike municipal wetland systems that typically have permits to discharge to surface water, constructed wetlands for treating livestock facility wastewater are generally not designed for discharge. Rather, the effluent from an animal waste constructed wetland is collected, stored, and then applied to the land or used for other purposes. The storage period may be the dormant season when wastewater cannot be land applied, or in warmer climates where year-round application occurs, it may simply be the planned period between applications.

(1) Dormant season storage

Wastewater, whether treated or not, must be stored during the dormant season when conditions do not allow its environmentally safe land application. Since a constructed wetland is capable of providing treatment, although at a reduced level, during the dormant season, its operation can continue even though the effluent cannot be immediately land applied. However, a downstream storage must be provided for the treated effluent generated during this period. On the other hand, if it is desired to operate the wetland only when

its treatment performance will be at or near optimum, the wetland's operation is ceased during the dormant season. This requires that the wastewater generated by the livestock operation be stored in a facility upstream of the wetland. Even then a storage facility downstream of the wetland may be needed.

Developing water budgets based on how the wetland will be managed is essential in determining this storage requirement. If the wetland is managed to be either empty or nearly empty at the beginning of the dormant season, the wetland itself may be capable of storing all or part of the precipitation falling on its surface and embankments. Downstream storage must be provided for the part the wetland itself cannot store. Of course, if the wetland is operated so it is at full depth at the beginning of the dormant season, downstream storage requirements will not be offset by storage capabilities of the wetland.

Operating the wetland during the dormant season will result in some reduction in treatment efficiency. This must be accounted for with a temperature adjustment factor in the Field Test Method of design. Design for cold weather operation must also counter the effects of freezing on pipes and on the overall hydraulics of the system.

(2) No dormant season storage (annual operation)

When the constructed wetland is operated for the entire year (annual operation), dormant season storage is not required upstream of the wetland. However, pretreatment ahead of the wetland is still needed to remove settleable solids and reduce the concentration of other pollutants. The volume of wastewater flow into the wetland is spread evenly over the year. Constructed wetland effluent storage would include that volume necessary to facilitate managing land application or other uses and provide management flexibility.

(c) Presumptive method

The presumptive method allows sizing a wetland when the animal production facility or pretreatment facility is not already on hand, and, hence, the actual concentrations of a given pollutant are not immediately known. In this case, design is based on estimates (presumptions) about the amount of a given pollutant that will enter the wetland on an average daily basis. Information on pollutant loads is derived from waste production tables and predicted levels of treatment occurring within a particular type of pretreatment facility. Such information is available in chapter 4 of the NRCS Agricultural Waste Management Field Handbook (2008) and other recognized technical sources. It should be noted that for an existing system where the addition of a constructed wetland is being considered, final planning and design should be made based on laboratory analysis of the pretreatment facility's effluent and with use of the field test method.

(1) Procedure

The following steps are taken to design a SF wetland using the presumptive method. Example 3–1 demonstrates calculations for each step. The size of the wetland for this example is based on nitrogen as being the controlling nutrient. The procedure is given for English units only. If different units are used than those suggested, appropriate conversions must be made.

Step 1 Estimate the average daily and annual TN loading to the constructed wetland, TN_d (lb TN/d) and TN_a (lb TN/yr).

A standard estimating technique, such as those provided in the USDA NRCS Agricultural Waste Management Field Handbook (1992) or other technical publications, should be used. The estimated influent TN is based on the amount of TN produced by the animals less losses occurring during handling, storage, or treatment prior to discharge to the constructed wetland.

Step 2 Determine cropland requirement to utilize TN_a loading (acres).

This step allows determination of whether further treatment of the proposed wetland is needed because of excess nutrients. If the computation shows that less acreage is needed based on nitrogen than is actually available, then no wetland is needed. However, the fact that the decisionmaker may have a goal that requires even more treatment than may be required for nutrient management should be noted and emphasized. For example, a high quality flushwater may be the goal.

The recommended method for determining the acreage needed for land application is to base it on soil tests and accompanying fertilization recommendations. If these recommendations are not available, an estimate can be made following the

nutrient budgeting procedures of AWMFH Chapter 11, Waste Utilization. Regardless of the method used, the losses occurring during application and the nutrients in the organic form that will not be available during the first year after application need to be considered.

Equation 3–1 may be used for this computation. The annual TN loading to the constructed wetland, TN_a, is in terms of pounds per year as determined in step 1. Crop TN requirement is in terms of pounds per acre per year determined as described above. The crop requirement is adjusted to compensate for losses by multiplying the crop requirement by the percentage remaining after losses occurring during application and those following application, such as leaching.

$$\text{Acreage} = \frac{TN_a}{\dfrac{\text{Crop TN requirement}}{\dfrac{\text{\%TN remaining after losses}}{100}}} \qquad \text{(eq. 3–1)}$$

Step 3 Estimate daily total TN required for the available cropland, N_i (lb/d).

The estimated total daily TN required for the available cropland, N_i, is determined by multiplying the available cropland acreage by the crop requirement adjusted to compensate for losses. The crop TN requirement is in terms of pounds per acre per year and is determined as described in step 2. Again, the crop requirement is adjusted for losses as described earlier.

$$N_i = \frac{\text{Available cropland} \times \text{Crop TN requirement}}{365\ \text{d/yr} \times \dfrac{\text{\% TN remaining after losses}}{100}} \qquad \text{(eq. 3–2)}$$

Step 4 Estimate the average daily constructed wetland influent volume, Q_d (gal/d).

Appropriate technical references and local climatic data are used to estimate the volume of wastewater to be discharged to the constructed wetland on a daily basis. Wastewater inputs to the wetland occur from such things as manure displacement, precipitation less evaporation on the surface from the pretreatment facility, precipitation, runoff, flushwater, and other inputs. Superior to making estimates based on published data is to measure the volume of wastewater generated.

Step 5 Calculate the average daily total TN effluent concentration needed from the wetland to satisfy daily input on the available acreage, C_e (mg/L).

Using the daily TN required for the available cropland, N_i, in terms of pounds per day (step 3), the average daily wastewater volume loading, Q_d, in gallons per day (step 4), and applying the appropriate conversion factors, the constructed wetland effluent N concentration (mg/L) is determined.

$$C_e = \frac{(N_i)(119{,}826)}{(Q_d)} \qquad \text{(eq. 3–3)}$$

where:

N_i = TN required for the available cropland (lb/d) – step 3

Qd = Average volume of wastewater entering the wetland daily (gal/d) – step 4

119,826 = conversion factor for lb/gal to mg/L

$$= \frac{\text{lb/d} \times 453592.4\ \text{mg/lb}}{\text{gal/d} \times 3.785412\ \text{L/gal}}$$

Step 6 Determine areal loading rate to the constructed wetland, LR (lb/a/d or kg/ha/d).

The following equation, in English or metric units as appropriate, is used to determine the constructed wetland areal loading rate (Payne and Knight 1998).

$$\text{English: } LR = 0.609(C_e) - 7.0$$
$$\text{Metric: } LR = 0.68(C_e) - 7.88 \qquad \text{(eq. 3–4)}$$

where:

LR = areal loading rate (lb/acre/d or kg/ha/d)

C_e = desired wetland effluent concentration (mg/L) – step 5

Equation 3–4 is not valid for values of C_e less than 11 mg/L. If such high levels of treatment are desired, possibly to meet discharge requirements, use of the Field Test Method is recommended.

Step 7 Determine surface area of the wetland (acres).

Determination of the surface area of the constructed wetland is based on the daily TN input

from the pretreatment facility in terms of pounds N per day (step 1) and the areal loading rate, LR, in terms of pounds per acre per day (step 6) using the equation:

$$\text{Surface area} = \frac{TN_d}{LR} \qquad \text{(eq. 3–5)}$$

The equation computes the water surface area for the wetland. The total area required by the constructed wetland is water surface area, embankment area requirement, and maintenance access area requirement.

Example 3–1 Solution using presumptive method

Given: A confined swine finishing facility that has 11,500 animals with an average weight of 135 pounds per animal live weight (LW). The wastewater will be pretreated in an anaerobic waste treatment lagoon with its supernatant containing 20 percent of the original as-excreted TN.

Annual volume of wastewater discharged to the wetland from the
waste treatment lagoon ....1,852,800 ft^3/yr
Cropland available for wastewater application....................80 acres
Crop requirement for TN per acre per year ....150 lb
Nitrogen application losses using sprinkler irrigation equipment ....25% (estimate) (table 11–6, AWMFH)
Losses of nitrogen through leaching ....5% (table 11–7, AWMFH)
Storage for effluent from the wetland ....45-day storage pond (results in an additional 10% nitrogen loss)

The proposed constructed wetland is in a climatic region that allows year-round operation. The phosphorus index determination indicates that wastewater may be applied on the basis of nitrogen as opposed to applying it based on phosphorus.

Required: The surface area for a constructed wetland to reduce nutrients as required for nutrient management.

Solution: *Step 1* Estimate the average daily and annual TN loading to the constructed wetland, TN_d (lb TN/d) and TN_a (lb TN/yr):

From the AWMFH, select an average daily production of 0.42 pound TN/1,000-lb LW.

$$\begin{aligned} TN_d &= (\text{Number of animals})(\text{Avg. LW})(TN_d \text{ production})(\text{N remaining}) \\ &= (11{,}500 \text{ hogs})(135 \text{ lb/hog})(0.42 \text{ lb TN/d/1,000 lb})(0.2) \\ &= 130.4 \text{ lb TN/d} \end{aligned}$$

$$\begin{aligned} TN_a &= (TN_d)(365 \text{ d/yr}) \\ &= (130.4 \text{ lb TN/d})(365 \text{ d/yr}) \\ &= 47{,}596 \text{ lb TN/yr} \end{aligned}$$

Example 3–1 Solution using presumptive method—Continued

Step 2 Determine cropland requirement to utilize TN_a loading, acres:

$$\text{Acreage} = \frac{TN_a}{\dfrac{\text{Crop TN requirement}}{\dfrac{(\text{\% TN remaining after losses})}{100}}}$$

$$= \frac{47{,}596 \text{ lb TN/yr}}{\left[\dfrac{(150 \text{ lb TN/acre/yr})}{\left\{\left(\dfrac{75}{100}\right)\left(\dfrac{95}{100}\right)\right\}}\right]}$$

=226 acres>80 acres of available cropland—a CW is needed

Note: TN remaining after losses for application is 100% – 25% loss = 75% and for leaching is 100% – 5% loss = 95%

Step 3 Estimate daily TN required for the available cropland:

$$N_i = \frac{\text{Available cropland} \times \text{Crop TN requirement}}{365 \text{ d/yr} \times \dfrac{\text{\% TN remaining after losses}}{100}}$$

$$N_i = \frac{(80 \text{ acres})(150 \text{ lb TN/acre/yr})}{(365 \text{ d/yr})\left(\dfrac{75}{100}\right)\left(\dfrac{95}{100}\right)\left(\dfrac{90}{100}\right)}$$

$$N_i = 51.3 \text{ lb TN/d}$$

Note: TN remaining after losses includes:
application losses—100% – 25% = 75%
leaching losses—100% – 5% = 95%
waste storage pond losses after CW treatment—100% – 10% = 90%

Step 4 Estimate the average daily constructed wetland influent volume: The annual volume of discharge to the constructed wetland is given as 1,852,800 ft^3/yr

$$Q_d = (1{,}852{,}800 \text{ ft}^3\text{/yr}) \times (1 \text{ yr/365 d}) \times (7.48 \text{ gal/ft}^3) = 37{,}970 \text{ gal/d}$$

Example 3–1 Solution using presumptive method—Continued

Step 5 Calculate the average daily TN concentration needed from the wetland to satisfy daily input for the available acreage, C_e:

$$C_e = \frac{(N_i)(119{,}826)}{(Q_d)}$$

$$= \frac{(51.3 \text{ lb TN/d})(119{,}826)}{(37{,}970 \text{ gal/d})}$$

$$= 162 \text{ mg/L}$$

Step 6 Determine areal loading rate to the constructed wetland, LR:

$$LR = 0.609(C_e) - 7.0$$

$$= [(0.609)(162 \text{ mg/L})] - 7.0$$

$$= 91.7 \text{ lb TN/acre/d}$$

Step 7 Determine surface area of the wetland:

$$\text{Surface area} = \frac{TN_d}{LR}$$

$$= \frac{(130.4 \text{ lb TN/d})}{(91.7 \text{ lb N/acre/d})}$$

$$= 1.42 \text{ acres}$$

$$= 1.42 \text{ acres} \times 43{,}560 \text{ ft}^2/\text{acre} = 61{,}855 \text{ ft}^2$$

For a wetland with a length to width ratio of 4:1, the required surface water dimensions of this wetland would be W = 124 ft and L = 497 ft.

Let x = width and 4x = length, then:

$$(4x)(x) = 61{,}855 \text{ ft}^2$$

$$x^2 = \frac{61{,}855 \text{ ft}^2}{4}$$

$$x = (15{,}463)^{0.5}$$

$$x = 124 \text{ ft}$$

$$\text{Length} = 4x$$

$$= (4)(124)$$

$$= 496 \text{ ft}$$

(d) Field test method

Field testing provides the most accurate way to determine the size of the wetland. Samples of the pretreatment wastewater are collected and analyzed, and the information is applied to the following equation for both English and metric units:

English unit:

$$A = -(0.305)\left(\frac{Q_a}{k_T}\right)\ln\left[\frac{(C_e - C^*)}{(C_i - C^*)}\right](365/t_{cw}) \quad \text{(eq. 3–6)}$$

Metric unit:

$$A = -\left(\frac{Q_a}{k_T}\right)\ln\left[\frac{(C_e - C^*)}{(C_i - C^*)}\right](365/t_{cw})$$

where:

A = wetted surface area of the wetland (ft^3 or m^3)
0.305 = factor to convert original metric equation
Q_a = annual flow into the wetland (ft^3/yr or m^3/yr)
k_T = $k_{20}\theta^{T-20}$, rate constant adjusted for temperature
k_{20} = 14 for TN, 10 for NH_4–N, and 8 for TP (m/yr)
θ = 1.06 for TN, 1.05 for NH_4–N, and 1.05 for TP (dimensionless)
T = average operating temperature (°C)
C_i = wetland influent concentration (mg/L)
C_e = wetland effluent concentration (mg/L)
C* = background concentration (mg/L), assumed to be 10 for TN and 3 for NH_4–N (based on a nationwide analysis of animal waste constructed wetlands)
365 = days of the year (d)
t_{cw} = days that the wetland will be in operation (i.e., the length of the growing season)

The basic equation (less the factor $365/t_{cw}$) was developed originally for municipal treatment wetlands (Kadlec and Knight 1996). Rate constants specific to animal waste constructed wetlands were developed from the national database on animal waste constructed wetlands (CH2M Hill and Payne 1997) and applied to the Kadlec and Knight equation, also called the k–C* model.

This model should be used where a pretreatment facility is already in place and samples can be readily collected. An alternative would be to collect samples from the pretreatment facility at a nearby facility that is expected to have the same characteristics (number of animals, size of pretreatment facility) and, therefore, the same wastewater characteristics.

Samples from the pretreatment facility are analyzed for the constituent of concern (TN, NH_4–N, or TP) to determine wetland influent concentration (C_i). In addition, the annual flow (Q_a) from the pretreatment facility must be calculated as well as the wetland effluent concentration for the nutrient of concern.

Average operating temperature used in the equation is based on the site temperatures when the constructed wetland will be actually operated. For example, if the constructed wetland is operated only during the growing season with the wastewater stored upstream through the dormant season, the temperature for the equation will be the average for the growing season. This, of course, will require that the stored volume of wastewater be treated in addition to what is generated during the growing season. Provisions for storage have been included in the equation with the factor $365/t_{cw}$.

The field test method differs from the original field test method presented in the NRCS technical requirement (USDA 1991) in that the size of the wetland is based on areal loading as opposed to volumetric loading. The same is true of both the original and new presumptive methods. (See prior information on areal versus volumetric loading and the information that follows the field test method example.)

(1) Procedure

The following steps are taken to determine the surface area for a SF wetland using the field test method. Subsequently, example 3–2 demonstrates the calculations for each step. This example uses English units. If metric units are desired, use the proper units and conversion factors for the equations chosen.

Step 1 Estimate the average daily and annual constructed wetland influent volumes, Q_d (gal/d and ft^3/d) and Q_a (ft^3/yr).

This step is the equivalent of step 4 in the presumptive method. Appropriate technical references and local climatic data are used to estimate the volume of wastewater to be discharged to the constructed wetland on a daily basis. Wastewater inputs to the wetland occur from such things as manure displacement, precipitation less evapora-

tion on the surface from the pretreatment facility, storm runoff water, flushwater, and other inputs.

Step 2 Estimate the average daily and annual TN loading to the constructed wetland, TN_d (lb TN/d) and TN_a (lb TN/yr).

This computation is based on laboratory results of pretreatment facility effluent and the volume of wastewater in gallons per day (step 1) entering the wetland.

$$TN_d = (Q_d)(TN_i)(8.34\times10^{-6})$$

where:

Q_d = average daily constructed wetland influent volume, gal/d (from step 1)
TN_i = wetland influent TN concentration, mg/L
8.34×10^{-6} = conversion factor for mg/L to lb/gal

$$TN_a = TN_d \times 365$$

Step 3 Determine cropland requirement to utilize the annual total N loading (acre).

This is the equivalent of step 2 in the presumptive method. If treatment for nutrient management is the goal of constructed wetland treatment, this step allows the determination of whether further treatment of the proposed constructed wetland is needed. If the computation shows that less acreage is needed based on nitrogen than is actually available, then no wetland is needed for nutrient concentration reduction. As noted in the presumptive method, the decisionmaker's goal may be something other than nutrient management. The goal could be to improve the water quality for such a purpose as a high quality flushwater or dust control. In such cases the issue as to whether the treatment of a constructed wetland is needed is not an issue and this step could be skipped.

The general equation for determining the cropland area requirement without a constructed wetland follows. The annual TN loading is determined by multiplying the daily TN loading to the constructed wetland in pounds of TN per day taken from step 2 by 365, the days in a year. The crop N requirement is best based on soil test and fertilizer recommendations. If these recommendations are not available, an estimate can be developed using the procedure in AWMFH chapter 11. The crop TN requirement is in terms of pounds of N per acre per year. Regardless of how the crop requirement is established, the amount must be adjusted for anticipated losses, such as from application and leaching. In the equation that follows, this is given as a percentage of TN remaining after the losses.

$$\text{Cropland requirement} = \frac{TN_a}{\text{Crop TN requirement} \times \frac{\%\text{ TN remaining after losses}}{100}}$$

TN_a is the annual TN loading in pounds per year (step 2), crop requirement in pounds per acre per year, and TN remaining after losses expressed as a percentage.

Step 4 Estimate daily TN required for the available cropland, N_i (lb/d).

This is the equivalent of step 3 in the presumptive method. The general equation for making this estimate follows. The crop TN requirement was established in step 3 as was the percentage of TN remaining after losses.

$$N_1 = \frac{\text{Available cropland} \times \text{Crop TN requirement}}{365\text{ d/yr} \times \frac{\%\text{ TN remaining after losses}}{100}}$$

Available cropland is in acres, crop TN requirement is in pounds N per acre per year, and TN remaining after losses is expressed as a percentage.

Step 5 Calculate the average daily total N effluent concentration needed from the wetland to satisfy daily input on the available acreage, C_e (mg/L).

Using the daily TN required for the available cropland in pounds per day, N_i, from step 4 and the average daily wastewater volume loading in gallons per day (step 1), the appropriate conversion factors are applied to determine the constructed wetland effluent N concentration (mg/L).

$$C_e = \frac{(N_i)(119{,}826)}{(Q_d)}$$

where:

N_i = daily total N required for the available cropland, lb/d (step 4)
Q_d = daily total N required for the available cropland, gal/d (step 1)
119,826 = conversion factor for lb/gal to mg/L

$$= \frac{\text{lb/d} \times 453592.4\text{mg/lb}}{\text{gal/d} \times 3.785412\text{L/gal}}$$

Step 6 Calculate k_T.

$$k_T = k_{20}\theta^{T-20} \quad \text{(eq. 3–7)}$$

where:

k_T = rate constant adjusted for temperature
k_{20} = 14 for total N and 10 for NH_4–N
θ = 1.06 for total N and 1.05 for NH_4–N (dimensionless)
T = average operating temperature (°C)

Step 7 Determine surface area of the wetland, A (ft^2).

$$A = -(0.305)\left(\frac{Q_a}{k_T}\right)\ln\left[\frac{(C_e - C^*)}{(C_i - C^*)}\right](365/t_{cw}) \quad \text{(eq. 3–6)}$$

where:

Q_a = annual flow into the wetland, ft^3/yr or m^3/yr (step 1)
C_i = wetland influent concentration, mg/L (from laboratory test results)
C_e = wetland effluent concentration, mg/L (step 5)
C* = background concentration (mg/L), assumed to be 10 for total N and 3 for NH_4-N based on a nationwide analysis of animal waste constructed wetlands
365 = days of the year, d
t_{cw} = days that the wetland will be in operation (i.e., the length of the growing season)

Step 8 Compute theoretical hydraulic detention time, t_d.

$$t_d = A \times D \times \frac{n}{Q_d}$$

where:

A = surface area of constructed wetland
D = depth of water in constructed wetland
n = wetland porosity
Q_d = average daily constructed wetland influent volume, gal/d

Step 9 Compute winter storage.

$$\text{Winter storage volume} = (365 - t_{cw})(Q_d)$$

where:

t_{cw} = days that the wetland will be in operation (i.e., the length of the growing season)
Q_d = average daily constructed wetland influent volume, gal/d

Example 3–2 Field test method solution

Given: The same confined swine finishing operation as the example for the presumptive method with the following additional information:

- Water depth in the constructed wetland is 8 inches. This depth is selected based on plant species to be used and other design factors.
- A wetland porosity, n, of 0.90
- The pretreatment effluent contains 412 mg/L of total nitrogen based on testing. Average temperatures for the site are as follows:

	May – Sept. (t_{cw}=150)	Apr. – Oct. (t_{cw}=210)	Mar. – Nov. (t_{cw}=270)	Jan. – Dec. (t_{cw}=365)
Average temp (°C)	24.6	22.5	20.3	17.1

Required: The surface area for a constructed wetland for April to October operation with the treatment goal of nutrient management to the available cropland.

Solution: *Step 1* Estimate the average daily and annual constructed wetland influent volumes:

$$Q_a = 1{,}852{,}800 \text{ ft}^3\text{/yr}$$
$$Q_d = 1{,}852{,}800 \text{ ft}^3\text{/yr} \times 1\text{yr/365 d} = 5.076 \text{ ft}^3\text{/d}$$
$$= 5{,}076 \text{ ft}^3\text{/d} \times 7.48 \text{ gal/ft}^3 = 37{,}970 \text{ gal/d}$$

Step 2 Estimate the average daily and annual total N loading to the constructed wetland: From the laboratory test results, the N concentration = 412 mg/L

$$TN_d = (Q_d)(\text{N concentration})(8.34 \times 10^{-6})$$
$$= (37{,}970 \text{ gal/d})(412 \text{ mg/L})(8.34 \times 10^{-6})$$
$$= 130.5 \text{ lb N/d}$$

$$TN_a = (TN_d)(365)$$
$$= (130.5 \text{ lb N/d})(365 \text{ d/yr})$$
$$= 47{,}632 \text{ lb N/yr}$$

Example 3–2 Field test method solution—Continued

Step 3 Determine cropland requirement to utilize the annual total N loading:

$$\text{Cropland requirement} = \frac{TN_a}{\text{Crop TN requirement} \times \frac{\text{\% TN remaining after losses}}{100}}$$

$$= \frac{47{,}632\text{lb N/yr}}{\left[\frac{(150\text{lb N/acre/yr})}{\left\{\left(\frac{75}{100}\right)\left(\frac{95}{100}\right)\right\}}\right]}$$

Step 4 Estimate daily total N required for the available cropland:

$$N_i = \frac{\text{Available cropland} \times \text{Crop TN requirement}}{365 \text{ d/yr} \times \frac{\text{\% TN remaining after losses}}{100}}$$

$$= \frac{(80 \text{ acres})(150 \text{ lb N/yr})}{(365 \text{ d/yr})\left(\frac{75}{100}\right)\left(\frac{95}{100}\right)\left(\frac{90}{100}\right)}$$

$$= 51.3 \text{ lb N/d}$$

Step 5 Calculate the average daily total N effluent concentration needed from the wetland to satisfy daily input on the available acreage:

$$C_e = \frac{(N_i)(119{,}826)}{(Q_d)}$$

$$= \frac{(51.3 \text{ lb N/d})(119{,}826)}{(37{,}970 \text{ gal/d})}$$

$$= 162 \text{ mg/L}$$

Step 6 Calculate k_T: For April to October

$$k_T = k_{20}\theta^{T-20}$$

$$= (14)(1.06)^{(22.5-20)}$$

$$= 16.2$$

Example 3–2 Field test method solution—Continued

Step 7 Determine surface area of the wetland: The surface area required for April to October operation:

$$A = -(0.305)\left(\frac{Q_a}{k_T}\right)\ln\left[\frac{(C_e - C^*)}{(C_i - C^*)}\right]\left(\frac{365}{t_{cw}}\right)$$

$$= -(0.305)\left(\frac{1,852,800\ \text{ft}^3}{16.2}\right)\left[\ln\left(\frac{162\ \text{mg/L} - 10\ \text{mg/L}}{412\ \text{mg/L} - 10}\right)\right]\left(\frac{365}{210}\right)$$

$$= (-34,883)\left[\ln\left(\frac{152\ \text{mg/L}}{402\ \text{mg/L}}\right)\right](1.74)$$

$$= (-34,883)\left[\ln(0.378)\right](1.74)$$

$$= (-34,883)(-0.9726)(1.74)$$

$$= 58,967\ \text{ft}^2$$

$$= \frac{58,967\ \text{ft}^2}{43,560\ \text{ft}^2/\text{acre}} = 1.4\ \text{acres}$$

Step 8 Compute theoretical hydraulic detention time, t_d:

$$t_d = \frac{A \times D \times (n)}{Q_d}$$

$$= \frac{(58,967\ \text{ft}^2)(8\ \text{in/12 in/ft})0.90}{5,076\ \text{ft}^3/\text{d}}$$

$$= \frac{(35,380\ \text{ft}^3)}{5,076\ \text{ft}^3/\text{d}}$$

$$= 6.9\ \text{days}$$

This satisfies the minimum requirement of 6.0 days. See NEH 637.0305(d).

Step 9 Compute winter storage requirement:

$$\text{Winter storage requirement} = (365 - t_{cw})(Q_d)$$

$$= (365 - 210)(5,076\ \text{ft}^3/\text{d})$$

$$= (155\ \text{d})(5,076\ \text{ft}^3/\text{d})$$

$$= 786,780\ \text{ft}^3$$

(2) Summary of field test method

Table 3–6 illustrates how different treatment periods used in the field test method affect wetland size for a given set of inflow and outflow concentrations of total nitrogen. The results are based on the same scenario as the design in example 3–2.

Values for hydraulic detention time (d_t) shown in this table are based on a wetland porosity (n) of 0.90, an average water depth of 8 inches, and a daily flow of 5,076 cubic feet per day. The wetland porosity is the volume of water not occupied by wetland plants and was originally assumed to be between 0.65 and 0.75. These values, from Reed et al. (1988), were used in the earlier NRCS field test method. However, TVA researchers found in one study that plant fill rates for cattails (*Typha* spp.) were 10 percent; bulrush (*Scirpus validus*), 14 percent; reeds (*Phragmites*), 2 percent; and woolgrass (*S. cyperinus*), 6 percent (Watson and Hobson 1989). In addition, Rogers et al. (1995) reported fill rates of 10 percent for *Sagittaria lancifolia* and 7 percent for *Phragmites australis*. These data indicate that fill rates presented in the earlier NRCS Technical Requirements (USDA 1991) were probably too high and, consequently, the values for wetland porosity were too low.

The earlier field test method (a volumetric method) required a determination of d_t, which meant that an accurate measure of water volume within the wetland be known. However, its value can be estimated with only a limited degree of accuracy (as was done in table 3–6). This is because mats of vegetation, growth habit of various plants, and other factors can reduce volume and either impede flow or cause short-circuiting. Estimates of d_t can be quite different from measurements using more sophisticated approaches, such as dye testing.

For the field test example, the wetland surface area or wetted area ranges from 1.1 to 1.7 acres, with treatment period and associated changes in temperature significantly affecting size. Of interest is that the area determined with the presumptive model, using the same number of animals with average weight of 135 pounds, was about 1.4 acres. This is the same as that calculated for a 210-day operating period for the field test model shown in example 3–2. This does not mean that the presumptive method and field test methods are considered comparable for any wetland with a 210-day storage period; it happens to be the same only because of the influent concentration selected for the field test example. If, for example, C_i for the field example had been 380 mg/L instead of 412 mg/L, with all other factors the same, the wetland surface area would have been 1.2 acres, while the presumptive method acres would remain at 1.4 acres.

Table 3–6 Example of wetland design criteria for an 11,500-head swine finishing facility for different treatment periods where Q_a = 1,852,800 ft^3/yr, C_i = 412, and C_e = 162

	May – Sept. (t_{cw}=150)	**Apr. – Oct. (t_{cw}=210)**	**Mar. – Nov. (t_{cw}=270)**	**Jan. – Dec. (t_{cw}=365)**
Average temp. (˚C)	24.6	22.5	20.3	17.1
k_T for TN (m/yr)	18.3	16.2	14.2	11.8
Wetland area (acre)	1.7	1.4	1.2	1.1
t_d (days) @ depth = 8 in	8.6	7.0	6.2	5.5
Winter storage (ft^3)	1,091,375	786,805	482,236	As needed for land application

(e) Designing for phosphorus removal

The presumptive method and the field test method can be used to design for P removal. The changes needed in the two models follow:

Presumptive method:

- Replace the loading rate equations in step 6 with the following:

  English: $LR = 0.49(C_e) + 0.51$

  Metric: $LR = 0.6(C_e) + 0.6$

  where:
  C_e = total phosphorus concentration in mg/L

- Replace other TN-based calculations with values for TP.

Field test method:

- Use the following values for TP in the equations in steps 6 and 7:

$$k_{20} = 8 \text{ m/yr}$$
$$\theta = 1.05$$
$$C^* = 2 \text{ mg/L}$$

(f) Wetland configuration

(1) Bottom gradient/maximum length

Early guidance on constructed wetlands indicated that a gradient in the lengthwise direction is beneficial to facilitate emptying the wetland for repairs or maintenance. While providing a gradient can facilitate emptying, the effect it will have on water depth should be considered. For instance, a wetland cell with a 0.5 percent grade and a water depth of 6 inches at the upstream end will have a water depth of 12 inches at a length of 100 feet and 15 inches at 150 feet. Therefore, if a bottom gradient is used, either by choice or out of necessity because of the site conditions, the maximum length is dependent on the allowable water depth for the wetland plants that will be used. If a level-bottom wetland is used, length is not an important consideration for most animal waste treatment wetlands. However, if large volumes of water are used and this water is pumped to a long, narrow wetland cell, resistance of the vegetation to the flowing water could cause incoming water to back up. At one municipal wetland having a 20:1 length-to-width ratio, flow was so restricted that wastewater overflowed the embankment at the inlet end of the system (Reed et al. 1995).

An acceptable alternative to providing a bottom gradient to facilitate emptying is a flat bottom with a deep zone that acts as a sump. The deep zone provides the submergence on the suction pipe necessary for the pump to transfer the wetland effluent to land application, to a downstream holding storage facility, or to an upstream waste treatment lagoon. If an exceptionally long, level bottom wetland is planned, intermediate deep zones should be used. This not only facilitates draining the wetland, but also allows effective lateral distribution of flow during normal operation.

(2) Layout of the wetland

The layout or configuration of a constructed wetland may be affected by site conditions. Shape of the site, area available, and lay of the land can influence how a constructed wetland is configured.

Surface-flow wetlands are generally designed to have more than one cell. For these multicelled wetlands, the cells are typically arranged in series (end-to-end) or in parallel (side-by-side). The parallel arrangement allows two or more cells to receive influent at the same time; thus, if the inlet on one cell plugs or if a cell is closed for maintenance, the other cell(s) can keep operating. The parallel arrangement can also be used for alternating treatment, allowing wetting and drying of cells and, thereby, enhancing treatment performance. However, this method of treatment requires a higher level of management. Figure 3–11 is a typical layout of cells in parallel.

An efficiently designed system has limited short-circuiting of wastewater between inlets and outlets. In the ideal system, wastewater flows evenly across the wetland cell throughout its entire length with no stagnant pools. An inlet consisting of a gated or slotted pipe across the upstream end helps to ensure initial distribution of flow. Figure 3–12 illustrates efficient and inefficient layouts as related to inlet and outlet structures. (More details about inlets follow.) As water moves through the plants and detritus, however, channelization of water may occur as a result of the buildup of islands of roots, rhizomes, and dead vegetation. For long, wide wetland cells, uneven distribution is more apt to occur, resulting in a need to redistribute flow. This can be accomplished by using shorter cells in series and discharging the effluent of one into

Figure 3–11 Typical layout of waste treatment lagoon/wetland/storage pond system

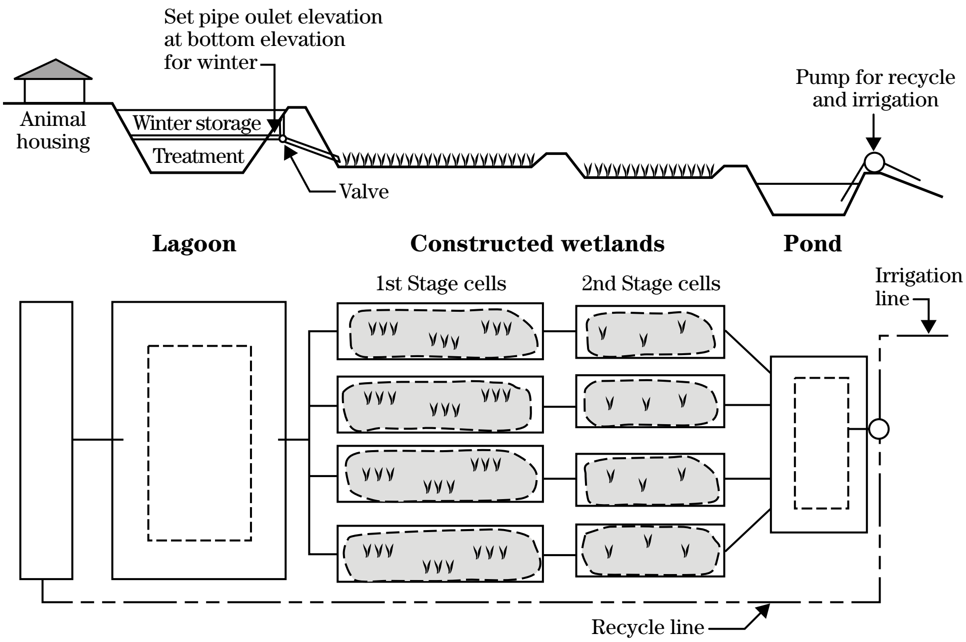
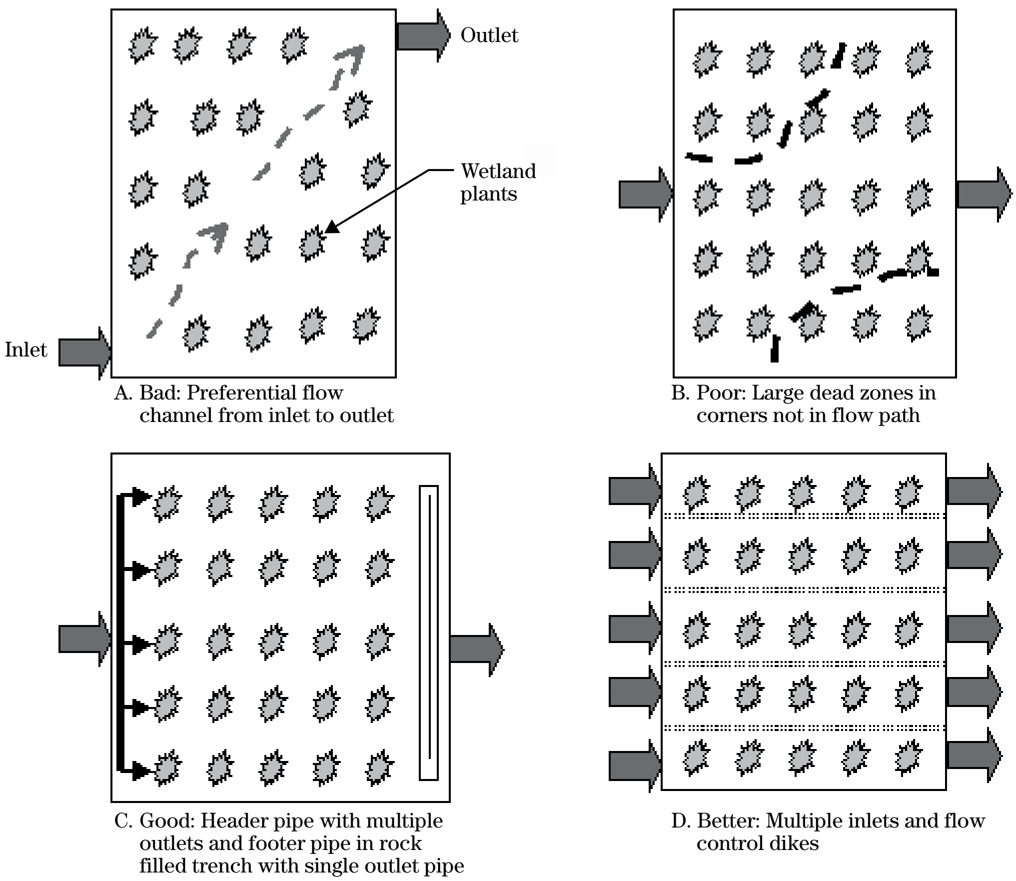


Figure 3–12 The effect of wetland layout configuration on effective flow distribution (modified from Kadlec and Knight 1997)



A. Bad: Preferential flow channel from inlet to outlet

B. Poor: Large dead zones in corners not in flow path

C. Good: Header pipe with multiple outlets and footer pipe in rock filled trench with single outlet pipe

D. Better: Multiple inlets and flow control dikes

a distribution header pipe or deep trench at the upstream end of a receiving cell. For long cells that have a flat bottom, flow can be redistributed laterally along the flow path by installing deep zones or trenches across the width of the cell at appropriate points. Inlet trenches and redistribution sumps should be at least 3 feet deeper than the constructed bottom of the cell to inhibit growth of rooted vegetation (Kadlec and Knight 1996).

As a rule, the length-to-width ratio for the system should be in the range of 1:1 to 4:1. Individual cells within this overall system may have ratios as high as 10:1. In fact, 20:1 length-to-width ratios have been used successfully. From the standpoint of construction costs, however, the square (1:1) wetland is most efficient. The cost advantage of the square wetland is offset by the critical need to provide for distribution of flow to prevent short-circuiting.

(g) Embankments

(1) Design height

Wetland embankments are often the same height. However, a distinction can be made between the outer embankments, which surround the entire system, and inner embankments or dikes that divide the system into cells. The outer embankment must be high enough to protect the system from overtopping during a specific design storm (i.e., 25-year, 24-hour). These embankments must have an ungated overflow device set at an elevation such that any precipitation that exceeds the design will pass through it.

Design height for the outer embankment should be based on the following increments of depth:

- normal design flow—based on type of vegetation; typically 8 to 12 inches
- accretion—based on buildup during the design life of the system; allow 0.5 inch per year
- design storm—includes direct precipitation on the wetlands plus runoff from embankments and, if inflow to the wetland is unrestricted, precipitation on the pretreatment surface, including embankments
- ice cover—If the system will operate under ice cover in winter, allow depth equal to ice thickness expected during some design period (i.e., once in 25 years)
- freeboard—A safety factor of at least 12 inches is recommended
- overflow device—As required by type (i.e., pipe, earthen spillway)

Design height for interior divider embankments must include at least the first three items listed for design height for outer embankment.

(2) Top width

The top width of dikes used to surround and divide the constructed wetland must be wide enough to accommodate the requirements of construction and operation and maintenance. Outer embankments should be at least 15 feet at the top to prevent burrowing animals from draining the system to the surrounding area. The recommended top width for inside dikes is 8 to 10 feet. This width allows grass to be mowed with tractor-driven equipment and reduces the potential for animals burrowing through the dikes. Narrower dikes or embankments must be cut with a hand mower and are easily breached by muskrats.

(3) Side slopes

Side slopes should not be steeper than 2 horizontal to 1 vertical. Consideration should be given to flatter slopes if needed for slope stability or to accommodate maintenance.

(h) Liners

The bottom of all wetland cells should be lined either with a compacted clay liner or with a fabricated liner if there is potential for groundwater contamination. Although the wetland operates under a low hydraulic head environment, seepage is still possible. A liner can help to avoid groundwater contamination by nitrates. Detailed information on evaluation of soils to protect groundwater is in the NRCS Agricultural Waste Management Field Handbook, appendix 10D.

If a fabricated liner is needed, the top 12 inches of soil from the construction site should be removed and stockpiled. After the liner has been installed, the stockpiled soil is placed on top of the liner to serve as the rooting medium for the wetland plants. To prevent puncture of the liner during construction, consider-

ation should be given to placing 6 to 8 inches of sand on top of the liner before installing the stockpiled soil. Overexcavation or additional fill height, or a combination of both, will be needed to accommodate the sand layer. Where a liner is installed, care must be taken to ensure that it ties in vertically at the embankments, thus preventing any lateral movement under or through the embankments. This requirement is the same for soil and fabricated liners.

(i) Inlet and outlet structures

(1) Inlet structures

A variety of inlet control structures can be used at constructed wetlands used to treat animal waste. They may include an ungated gravity flow overflow pipe from the pretreatment facility to the first cells of the constructed wetland, pipes with orifice controls, swivel pipes, and valves.

Inlets may discharge at a point centered on the width of the upstream end of the cell if the cells are relatively narrow and dead zones will not be a problem in the adjacent corners. Gated pipe that spans the width of the cell can ensure even distribution and eliminate dead zones in the corners. This pipe has precut holes or slots, or it may have gated openings so flow can be more accurately distributed. Plugging is sometimes a problem at the inlet to the first cell where influent wastewater is from the pretreatment facility. If this is a concern, an alternative to a gated pipe is a deep trench across the width of the upper end of the cell. An elbow can be placed on the inlet pipe so that influent water is discharged downward into the middle of the trench; wastewater should then discharge into the vegetation across the width of the cell. If the cell is wide, a shallow dam with multiple slots or weirs across the top can be placed immediately downstream of the trench.

If wastewater will be stored in the pretreatment facility during winter, the invert elevation at the entrance to the effluent pipe leading to the wetland should be in line with the bottom elevation of winter storage. If the design calls for winter storage in the upstream pretreatment facility, some positive control is needed to prevent discharge to the wetland during this period (i.e., a closed valve). In addition, some positive control is also needed to ensure that stored wastewater is released to the wetland according to a water budget for the system. This may mean manually opening and closing of valves on a daily basis or using a properly sized orifice control based on daily requirements of the water budget. **Note:** Reliance on manually opening and closing valves can be a dangerous option because the operator may forget to close a valve, which could result in a discharge from the system.

All control devices should be checked daily since plugging of pipes and controls can be a problem. A buildup of a crystalline substance on pipe walls is a problem in some orifice-control devices. An inlet screen or box screen used around the inlet pipes to the first cell can prevent floating debris from entering the line. Small turtles have been known to enter an unprotected inlet and clog the pipe. For these reasons, large diameter pipe is preferred over smaller diameter pipe.

(2) Outlet structures

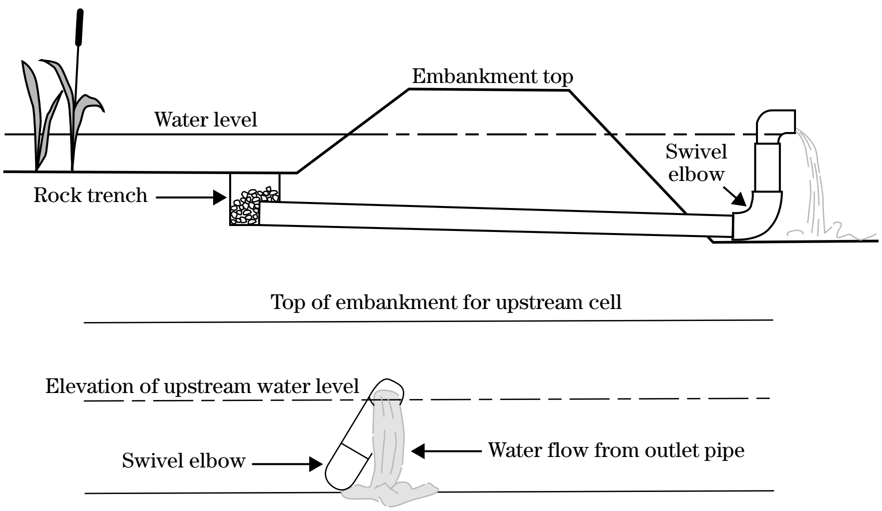
The outlet structure is used to maintain the proper water level in the upstream cell and to control flow rate. Several types of outlet controls are possible. They include slotted pipes laid across the downstream end of the cell or slotted pipes buried in a shallow trench of gravel. In each case a T-section is placed in the middle of the pipe to carry water through the embankment to a water-level control structure.

The most common water-level control structure used on wetlands for treating animal waste is an elbow attached with a swivel joint located downstream of the cell for which water level is being controlled (fig. 3–13). In other words, water level in the upstream cell will be at the same elevation as the invert of the downstream outlet pipe. As the pipe is turned on the swivel, the invert of the pipe is raised or lowered, thus setting water depth in the upstream cell.

Water can be discharged to a point centered on the width of the upstream end of the next cell if the cell is relatively narrow. If it is wider and there is concern for dead zones in the corners (fig. 3–12), the swivel pipe can be attached to a header pipe, forming a U between the pipe that exits the embankment and the header.

Another water level control device is a flashboard dam. This provides a simple way to control upstream water level without the problem of plugging pipes. However, the embankment on the downstream side must be adequately protected from erosion, and a deep-zone distribution trench may be needed if the downstream cell is wide.

Figure 3–13 Typical configuration of a water-level control structure



(j) Water budget

A water budget is essential as it is used in:

- determining annual and daily flow rates needed to determine wetland surface area using the presumptive and field test design equations
- sizing the embankments
- scheduling land application
- determining release rates or pumping rates to the wetland for the in-use period, and sizing pipes, pumps, orifice controls, and other devices accordingly
- sizing the downstream storage pond
- sizing storage for the upstream pretreatment facility
- determining detention time in the wetland

If several treatment wetlands will be designed, a computer spreadsheet is recommended to speed repetitive calculations and assist with accuracy in design. A sample spreadsheet is shown in table 3–7.

(k) Operation and maintenance

Written operation and maintenance (O&M) requirements for a constructed wetland must be incorporated into the AWMS plan to which the wetland becomes a component. In addition to the O&M requirement for the wetland itself, coordination of its operation with other components of the AWMS must also be described. For further information on development AWMS plan see AWMFH, Chapter 13, Operation, Maintenance, and Safety. Recommended requirements to be included in the AWMS plan for a constructed wetland are described in this section.

(1) Operation

Operation of a constructed wetland includes the administration, management, and performance of non-maintenance actions needed to keep the wetland safe and functioning as planned. Annual operational requirements are dictated by the water budget, by visual inspection, by wastewater testing, and by common sense. Some key operational requirements include:

- Maintaining water levels in the wetland cells as appropriate for the vegetation. In cold climates where continuous winter operation is involved, increase water levels as needed prior to the first freeze.
- Controlling flows into the wetland in accordance with water budget requirements. Adjust as needed for drought periods, increasing inflow rates to ensure vegetation at the downstream end of the wetland is kept wet during dry times.

- Ensuring that water levels in the pretreatment facility and downstream storage pond are lowered to appropriate levels in preparation for winter storage.
- Monitoring treatment performance. Collect samples and measure flow rates into and out of the wetland regularly. Determine treatment efficiencies and nutrient mass loadings for use in adjusting application rates. Typically, samples should be analyzed for total Kjeldahl nitrogen (TKN), total ammonia nitrogen (NH_3 + NH_4–N), combined nitrite plus nitrate nitrogen (NO_2 + NO_3–N), total phosphorus (TP), and ortho-phosphorus (ortho-PO_4–P). If a wastewater discharge is being considered or if additional information on water quality improvement is sought, 5-day biochemical oxygen (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), temperature, and pH may be required by the State regulatory agency.

(2) Maintenance

Maintenance of a constructed wetland includes actions taken to prevent deterioration of the wetland components and to repair damage. Regular maintenance of the wetland system is essential. If frequent inspections are ignored, rodents can destroy vegetation and embankments, pipes can become clogged, wastewater can short circuit through the cells, and the system can become nonoperational in a short time.

A short list of important maintenance items follows. This is not intended to be an all-inclusive list:

Table 3–7 Sample water balance spreadsheet for 2,000 finisher swine with 400- by 400-foot waste treatment lagoon and 26,400-square foot constructed wetland

Climate	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Precip.	5.60	5.40	6.00	5.90	4.90	5.00	4.50	4.00	3.80	4.20	5.00	5.20	59.50
Pan Evap.	3.20	3.80	4.00	4.00	4.30	5.10	5.60	6.20	4.90	4.30	4.00	3.80	53.20
Lake Evap.	2.20	2.70	2.80	2.80	3.00	3.80	3.90	4.30	3.40	3.00	2.80	2.70	37.40
Items Input						Volume (1,000 ft³/mo)							
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Manure	11.20	10.10	11.20	10.80	11.20	10.80	11.20	11.20	10.80	11.20	10.80	11.20	131.70
Precip. lagoon	74.70	72.00	80.00	78.70	65.30	66.70	60.00	53.30	50.70	56.00	66.70	69.30	793.40
Precip. CW	12.30	11.90	13.20	13.00	10.80	11.00	9.90	8.80	8.40	9.20	11.00	11.40	130.90
Flush [1/]	0.00	0.00	0.00	120.30	124.30	120.30	124.30	124.30	120.30	0.00	0.00	0.00	733.80
Runoff	4.70	4.50	5.00	4.90	4.08	4.17	3.75	3.33	3.16	3.50	4.16	4.33	49.58
Total	102.90	98.50	109.40	227.70	215.68	212.97	209.15	200.93	193.36	79.90	92.66	96.23	1,839.38
Output	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Evap. - lagoon	29.90	35.50	37.30	37.30	40.10	47.60	52.20	57.80	45.70	40.10	37.30	35.50	496.30
Evap. CW	4.93	5.85	6.16	6.16	6.62	7.85	8.62	9.55	7.55	6.62	6.16	5.85	81.92
							Net Annual w.w. = Total input = Total output						
Land application (1,000 ft³)	0	0	0	210.19	210.19	210.19	210.19	210.19	210.19	0	0	0	1,261.16

1/ Fresh flushwater at 15 gal/head/day. If recycled wastewater from the constructed wetland is used, flush = 0.

- Inspect inlet and outlet structures daily for plugging and damage.
- Inspect embankments at least weekly for damage, and make repairs as needed. Control rodent pests through removal or deterrents, such as electric fences.
- Mow embankments regularly to allow for inspections and to enhance visual appeal.
- Inspect and repair fences as needed.
- Inspect vegetation throughout the growing season, and replace plants that are not performing as expected.
- Inspect and repair pumps and piping systems as needed.

637.0307 Plant establishment and maintenance

Successful plant establishment requires adequate soil preparation, intact plant materials, appropriate plant spacing, proper planting methods, good timing, sufficient soil moisture, and proper water depth. Failure to provide any of these can be problematic to establishment of a successful wetland planting. Wetland vegetation maintenance by comparison to initial plant establishment is not nearly as simple. Perpetuation of dominance by desired species, maintenance of desired plant cover density, and exclusion of undesirable plant species are all complex, problematic goals that cannot always be achieved (Kadlec and Knight 1996).

(a) Plant sources

In recent years, commercial supplies of wetland plant material have become relatively common. Regulations requiring entities that remove or manipulate wetlands to mitigate the wetland losses have created a high demand for live, healthy plants for revegetation. Most commonly used plants for treatment wetlands can be purchased for planting or can be harvested locally from existing roadside ditches or pond margins. Depending on the morphology of individual plants, the plant can be purchased as a bare-root seedling, a sterile propagule from a micropropagation laboratory, a senesced root or rhizome, a potted seedling, or an individual taken from an established stand. Some wetland plants can be established from seed. Seeds can be planted by hand broadcasting or automated broadcasting using a tractor.

Another method of establishing plants in a newly constructed wetland is reliance on volunteer colonization from an existing or imported seed bank. Most constructed treatment wetlands require some type of organic soil augmentation for successful plant establishment. Removing a layer of soil from another existing wetland and evenly distributing the soil throughout the newly constructed wetland allow the natural seed bank in the existing soil to germinate and establish the vegetation in the new treatment wetland.

The most common form of plant seedlings is bare-root propagules. Bare-root seedlings are easily planted in

the field using a small shovel, trowel, or dibble. The survival rate of bare-root seedlings is significantly higher than that for field germinated seeds and generally can be maintained at 80 percent or higher with healthy plant stock and an adequate moisture regime. Since bare-root stock has already had a sufficient period of initial growth, successful planting can lead to a rapid plant cover.

Field-harvested plants, in some cases, offer the most successful option for planting treatment wetlands. These plants can be collected in nearby retention ponds, roadside ditches, and canals and then planted in suitable substrate in the newly constructed wetland. Planting of field-harvested plants may be more difficult than planting bare-root propagules because of the size differences of the plants. Planting can be accomplished by using a shovel or post-hole digger to bury all roots and associated belowground structures. Stresses to the plants, such as extreme shifts in temperature, moisture, and light, should be limited where possible. The advantages of field-harvested plants over nursery grown stock (Kadlec and Knight, 1996) include:

- Larger roots, rhizomes, and/or corms for energy storage allow the plant to produce aboveground structures faster once they are planted.
- They are adapted to local environmental conditions.
- Additional volunteer plant species are introduced with the harvested plant species

(b) Plant establishment

Wetland plants have various environmental adaptations as part of their normal routines of germination, growth, reproduction, and senescence/decay. A general understanding of these components of plant biology is important in planning and operating constructed wetlands.

Most emergent wetland plants produce seeds that germinate and initially develop best in wet, but unflooded loamy soil. Excessive flooding kills most wetland plant seedlings. Tight, clayey soil may be inhospitable for root development and aeration. Highly drained sandy soil and gravel may not provide adequate moisture for initial plant development. Rapid development of herbaceous wetland plants in many constructed wetlands is normally accomplished through adequate spacing of healthy plants into moist, loamy to sandy soil, followed by gradual increases in the water level during plant establishment. Rapid increases in water level within newly planted treatment wetlands may kill the plantings.

Plants require nutrients in proper proportions for healthy growth. The two major nutrients most likely to limit plant growth in wetlands are phosphorus and nitrogen, respectively. Other nutrients especially important for plant growth are carbon (typically supplied from atmospheric or dissolved carbon dioxide), potassium, calcium, and sulfur. In addition, wetland plants require several minor nutrients for normal growth and development. Some essential plant micronutrients are magnesium, iron, manganese, boron, zinc, copper, and molybdenum. While livestock wastewater supplies adequate quantities of these nutrients, some industrial wastewater and agricultural runoff water do not provide ample nutrition for productive wetland plant growth. In such cases nutrient supplements may be required for rapid plant development and for sustained wetland plant growth. Soil tests during predesign can identify fertilization requirements for rapid plant establishment. In a relatively few instances, supplements of plant micronutrients must be added to wetlands to provide adequate plant growth.

(c) Plant maintenance

Wetland plant species have a variety of growth strategies that provide a competitive advantage in their natural habitats. Emergent herbaceous marsh species in temperate climates generally grow vegetatively within a single growing season to a maximum total standing live biomass in late summer or early fall. This biomass may represent multiple growth and senescence periods for individual plants during the course of the growing season, or a single emergence of plant structures. Standing senesced biomass provides attachment sites for microbial species important in wetland treatment performance throughout the annual cycle. It is also important for maintaining root viability under flooded, winter conditions.

Excess solids can stress or kill wetland plants. Since untreated livestock wastewater typically contains high concentrations of solids, adequate pretreatment of the wastewater is important. This can be accomplished by

settling solids in lagoons or storage ponds or by using special solids separators.

Other environmental factors that may stress the wetland plants include excessive water depth (any constant depth over about 12 to 18 inches is stressful to emergent wetland plants), excessive drought conditions, extremely hot or cold conditions, insect pests, and plant pathogens. Some emergent wetland plant species, such as cattails, can quickly recover from pest outbreaks and excessive water levels if their roots remain alive and healthy and conditions become more favorable. Healthy wetland plant communities that senesce during freezing winter conditions quickly regrow from belowground structures during the next growing season as long as their standing dead stems remain above the water level during the nongrowing season.

637.0308 References

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Glossary

Accretion Refers to the long-term buildup of a peat-like material consisting of settleable solids from the waste stream, the remnants of decayed plant litter, and microbial biomass on the floor of a surface flow wetland or on top of the filter bed of a subsurface flow wetland.

Adsorption The process by which chemicals are held on a solid surface, such as the positively charged ammonium ion (NH_4+) bonding with negatively charged clay particles.

Aerobic Living, active, or occurring only in the presence of free oxygen. A condition of having free oxygen.

Agricultural waste management system A combination of conservation practices formulated to appropriately manage a waste product that, when implemented, will recycle waste constituents to the fullest extent possible and protect the resource base in a nonpolluting manner.

Agricultural waste Waste normally associated with the production and processing of food and fiber on farms, feedlots, ranches, and forests that may include animal manure, crop and food processing residue, agricultural chemicals, and animal carcasses.

Algae Photosynthetic organisms that occur in most habitats, ranging from marine and freshwater to desert sands and from hot boiling springs to snow and ice. They vary from small, single-celled forms to complex, multicellular forms, such as the giant kelps of the eastern Pacific that grow to more than 60 meters in length and form dense marine forests.

Ambient Environmental or surrounding conditions.

Ammonification The production of ammonia by microorganisms through the decomposition of organic matter.

Anaerobic Living, active, or occurring only in the absence of free oxygen. A condition of being without free oxygen.

Anoxic sediment Sediment devoid of oxygen.

Biochemical oxygen demand (BOD) The amount of oxygen (measured in mg/L) required in the oxidation of organic matter by biological action under specific standard test conditions. Widely used to measure the amount of organic pollution in wastewater and streams.

Biomass The total mass of living tissue of both plants and animals.

BOD_5 Biochemical oxygen demand measured over a standard 5-day test period; distinguished from BOD_N (nitrogenous oxygen demand) and BOD_U (ultimate oxygen demand). See Biochemical oxygen demand.

Cation exchange The interchange between a cation in solution and another cation in the boundary layer between the solution and surface of negatively charged material, such as clay or organic matter.

Center pivot An automated irrigation system consisting of a sprinkler line rotating about a pivot point at one end and supported by a number of self-propelled towers. The water is supplied at the pivot point and flows outward through the line supplying the individual outlets.

Chelation A chemical complexing (forming or joining together) of metallic cations with certain organic compounds.

Class A pan evaporation Evaporation as measured using a standard U.S. Weather Bureau Class A evaporation pan that has a depth of 10 inches and a diameter of 48 inches. The depth of water that evaporates is measured, and coefficients can be applied to estimate evaporation amounts from waterbodies. A typical coefficient for lakes is 0.7.

Complexation A reaction in which a metal ion and one or more anionic ligands chemically bond. Complexes often prevent the precipitation of metals.

Composting A facilitated process of aerobic biological decomposition of organic material characterized by elevated temperature that, when complete, results in a relatively stable product suitable for a variety of agricultural and horticultural uses.

Constructed wetland A shallow, earthen impoundment containing hydrophilic vegetation designed to treat both point and nonpoint sources of water pollution.

Culm An aerial stem bearing the inflorescence, in grasses, rushes, and other such plants.

Deciduous Plants that shed all their leaves annually, generally in the fall.

Decisionmaker An individual, group, unit of government, or other entity that has the authority by ownership, position, office, delegation, or otherwise to decide on a course of action.

Denitrification Reduction of nitrogen oxides (usually nitrate and nitrite) to molecular nitrogen or nitrogen oxides with a lower oxidation state of nitrogen by bacterial activity (denitrification) or by chemical reactions involving nitrite (chemodenitrification). Nitrogen oxides are used by bacteria as terminal electron acceptors in place of oxygen in anaerobic or microaerophilic respiratory metabolism.

Diffusion The process by which matter, typically a gas, is transported from one part of a system to another as the result of random molecular movement; movement is from areas of high concentration to areas of low concentration influenced by temperature and the nature of the medium.

Dissolved oxygen (DO) The molecular oxygen dissolved in water, wastewater, or other liquid; generally expressed in milligrams per liter, parts per million, or percent of saturation.

Effluent Water or some other liquid—raw, partially or completely treated—flowing from a waste storage or treatment facility.

Emergent plant An aquatic or wetland plant with its lower part submerged and its upper part extending upright above the water.

Evapotranspiration (ET) The combination of water transpired from vegetation and evaporation from soil and plant surfaces. Sometimes called consumptive use.

Facultative species In the context of wetland plants, the term refers to species of plants that can grow under natural conditions in both wetlands and uplands. See Obligate species.

Field test method An approach to sizing constructed wetlands based on loading determined from laboratory test results of the influent proposed for the wetland.

Floating aquatic plants Aquatic plants that are not attached to the soil, but rather float freely on or near the water surface, such as duckweed and water hyacinths.

Floating aquatic plant (FAP) systems Consists of a pond or series of ponds in which floating aquatic plants are grown for the purpose of treating wastewater.

Flushwater Water used to clean or rinse surfaces.

Free-floating plants Plants that float at or beneath the water surface without attachment to the substrate. Free-floating aquatics are transported freely by wind and currents, so they are normally found in abundance only in calm, sheltered water. Duckweed (*Lemna* spp.), bladderwort (*Utricularia vulgaris*), and coontail (*Ceratophyllum demersum*) are common examples of free-floating aquatics.

Gated pipe Portable pipe that has small gates installed along one side for distributing water across the width of the inlet end of a constructed wetland cell or to surface irrigation corrugations or furrows.

Groundwater Water that flows or seeps downward and saturates soil or rock, supplying springs and wells. The upper level of the saturated zone is called the water table. Water stored underground in rock crevices and in the pores of geologic material that makes up the Earth's crust. That part of the subsurface water that is in the zone of saturation; phreatic water.

Herbaceous vegetation Plants that are herbs with soft, nonwoody stems and no secondary growth.

Hydraulic detention time The period that wastewater flow is retained in the constructed wetland for completion of physical, chemical, or biological reaction. The theoretical detention time is equal to the volume of water in the constructed wetland divided by the flow rate.

Hydraulic gradient The slope of the surface of open or undergroundwater.

Hydrophytic vegetation Any plant that can grow in water or on a substrate that is at least periodically deficient in oxygen as a result of excessive water content.

Influent Water or other liquid—raw or partly treated—flowing into a reservoir, basin, treatment process or treatment plant.

Ion An electrically charged atom, radical, or molecule formed by the loss or gain of one or more electrons.

Ion exchange A process that involves substitution of one ion, either cation or anion, for another of the same charge when a solution containing ions is passed into a molecular network having either acidic or basic substituent groups that can be readily ionized. The ions in the solution attach themselves to the network, replacing the acidic or basic groups.

Jurisdictional wetlands Those wetlands defined as water of the United States. They include all that are currently used or were used in the past or may be susceptible to use in interstate commerce, including: all water that is subject to ebb and flow of the tide; all interstate water including interstate wetlands; all other water, such as intrastate lakes, rivers, streams including intermittent streams, mudflats, sandflats, wetlands, sloughs, prairie potholes, wet meadows, playa lakes, or natural ponds, the use, degradation, or destruction of which would or could affect interstate or foreign commerce; all impoundments of water otherwise defined as water of the United States under this definition; tributaries of water defined above; the territorial sea; and wetlands adjacent to water (other than water that is itself wetlands) identified above. See Wetlands.

Kjeldahl nitrogen Nitrogen in the form of organic proteins or their decomposition product ammonia, as measured by the Kjeldahl Method.

Lacuna A gap or cavity.

Lake evaporation The rate of evaporation from a water surface like that of a lake too large to be much affected by the additional evaporation that occurs at the edge.

Land application Application of manure, sewage sludge, municipal wastewater, and industrial wastewater to land for reuse of the nutrients and organic matter for their fertilizer and soil conditioning value.

Leaching The removal of soluble material from one zone in soil to another via water movement in the profile.

Lenticel A small, raised, corky spot or line appearing on young bark, through which gaseous exchange occurs.

Liner A relatively impermeable barrier designed to prevent seepage into the soil below. Liner material includes plastic and dense clay.

Livestock Animals kept or raised for use or pleasure, especially farm animals kept for use and profit, includes cattle, swine, poultry, and horses.

Loading The quantity of a substance entering the environment or facility, such as the quantity of a nutrient to a constructed wetland.

Macrophyte A macroscopic vascular plant; a multicellular aquatic plant, either free-floating or attached to a surface.

Nonpersistent plant A plant that breaks down readily after the growing season.

Nonpoint source Pollution sources that are diffuse and do not have a single point of origin or are not introduced into a receiving stream from a specific outlet.

Nutria Aquatic, plant-eating rodent, *Myocastor coypus*, native of South America, resembling a small beaver with a ratlike tail. These rodents inhabit wetlands throughout the continental United States and are considered destructive pests.

Nutrient Elements or compounds essential as raw material for organism growth and development.

Obligate species Species that in nature can grow and multiply in only specific environment.

Organic matter Mass of matter that contains living organisms or nonliving material derived from organisms. Sometime refers to the organic constituents of soil.

Oxidation The addition of oxygen, removal of hydrogen, or the removal of electrons from an element or compound. In the environment, organic matter is oxidized to more stable substances.

Pathogen Microorganisms that can cause disease in other organisms or in humans, animals, and plants. They may be bacteria, viruses, fungi, or parasites.

Perennial plant A plant that lives through several growing seasons.

Point source A stationary location or fixed facility from which pollutants are discharged or emitted.

Presumptive method An approach to sizing a constructed wetlands based on estimates of influent loadings.

Pretreatment Treatment of waste or wastewater to reduce the concentrations of solids and other constituents of waste and wastewater before discharge to a facility for further management.

Propagules Any of various portions of a plant, such as a bud or other offshoot, that aid in dispersal of the species and from which a new individual may develop.

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

Seepage The loss of water by percolation into the soil from a canal, ditch, lateral, watercourse, reservoir, storage facility, or other body of water, or from a field.

Senescence The plant growth phase from full maturity to death that is characterized by an accumulation of metabolic products, increase in respiratory rate, and loss in dry weight, especially in leaves and fruit.

Settleable solids Solids in a liquid that can be removed by stilling a liquid. Settling times of at least 1 hour are generally used.

Short circuiting When water finds a more direct course from inlet to outlet than was intended. This is generally undesirable because it may result in short contact, reaction, or settling time in comparison with the theoretical or presumed detention times.

Sludge The accumulation of solids resulting from chemical coagulation, flocculation, and sedimentation after water or wastewater treatment.

Solids See Total solids.

Solid set system An irrigation system that covers the complete field with pipes and sprinklers in such a manner that all the field can be irrigated without moving any of the system.

Sorption The removal of an ion or molecule from solution by adsorption and absorption. It is often used when the exact nature of the mechanism of removal is not known.

Stolon A trailing aboveground stem or shoot, often rooting at the nodes and forming new plants.

Substrate A supporting surface on which organisms grow. The substrate may simply provide structural support, or may provide water and nutrients. A substrate may be inorganic, such as rock or soil, or it may be organic, such as vegetation surfaces.

Subsurface flow (SSF) wetlands Constructed wetlands consisting of a bed of gravel, rock, or soil media through which the wastewater flows. Emergent, hydrophytic vegetation is planted at the surface of the wetland. The water surface is maintained at an elevation just below the surface of the bed.

Supernatant The liquid fraction in a waste impoundment, such as a waste treatment lagoon or waste storage pond, that overlies the sludge or settled solids.

Surface flow (SF) wetlands A constructed wetland consisting of shallow earthen basin planted with rooted, emergent vegetation in which water flows across the soil surface.

Suspended solids Organic or inorganic particles that are suspended in and carried by the water. The term includes sand, mud, and clay particles, as well as solids in wastewater.

TKN Total Kjeldahl nitrogen. See Kjeldahl nitrogen.

Total maximum daily load (TMDL) The sum of the individual wasteload allocations for point sources and load allocations for nonpoint sources and natural background.

Total solids The weight of all solids, dissolved and suspended, organic and inorganic, per unit of volume of water or wastewater. It is the residue remaining after all water has been removed by evaporation.

Traveling gun An irrigation system using a high volume, high pressure sprinkler (gun) mounted on a trailer, with water being supplied through a flexible hose or from an open ditch along which the trailer passes.

Treatment Chemical, biological, or mechanical procedures applied to sources of contamination to remove, reduce, or neutralize contaminants.

Tuber An enlarged, fleshy, underground stem with buds capable of producing new plants.

Vascular plants Plants that possess a well-developed system of specialized tissues that conduct water, mineral nutrients, and products of photosynthesis through the plant, consisting of the xylem and phloem.

Venn diagram A diagram where sets are represented as simple geometric figures, with intersections and unions of sets represented by intersections and unions of the figures.

Volatile solids That part of total solids driven off as volatile (combustible) gases when heated to 1,112 degrees Fahrenheit.

Volatilization Loss of gaseous components, such as ammonium nitrogen, from animal manure.

Waste storage facility A waste storage impoundment made by constructing an embankment and/or excavating a pit or dugout or by fabricating a structure for the temporary storage of animal or other gricultural waste.

Waste treatment lagoon A waste treatment impoundment made by constructing an embankment and/or excavating a pit or dugout for the biological treatment of animal and other agricultural waste.

Wastewater The used water and solids from a confined livestock or aquaculture facility that is usually not suitable for reuse unless it is treated.

Water budget An accounting of the inflow to, outflow from, and storage changes of water in a hydrologic unit.

Water quality The excellence of water in comparison with its intended use or uses.

Water table The upper surface of groundwater in the zone of saturation.

Wetland porosity The amount of wetland water volume not occupied by plants, expressed as a decimal.

Wetlands Land transitional between terrestrial and aquatic systems that has a water table at or near the surface or a shallow covering of water, hydric soil, and a prevalence of hydrophytic vegetation. Note that there are several versions of this definition. Refer to agency definitions (USEPA/Army Corps of Engineers, U.S. Fish and Wildlife Service) for a more precise definition.

Appendix 3A Typical Aquatic and Wetland Plant Species Used in Constructed Wetlands

(From *Constructed Wetlands for Animal Waste Treatment, A Manual on Performance, Design, and Operation with Case Histories*, Gulf of Mexico Program, Nutrient Enrichment Committee, June 1997; adapted with modifications from Thunhorst (1993))

Plant species	Common name	Growth form	Persistence	Rate	Method	Spacing
Acer negundo	Box elder	Tree	Perennial, deciduous	Fast, 4.5 to 6 m in 5 yr		
Acer rubrum	Red maple	Tree	Perennial, deciduous	Medium to fast, 5 to 7 m in 10 yr		
Acorus calamus	Sweet flag	Emergent, herbaceous	Perennial, nonpersistent	Moderate, 15 cm/yr	Rhizome	0.3 to 0.9 m O.C.
Alnus serrulata	Smooth alder	Shrub	Perennial, deciduous	Rapid, 60 cm/yr		
Carex spp.	Sedges	Emergent, herbaceous	Perennial, nonpersistent	Slow to rapid	Rhizome	0.15 to 1.8 m O.C.
Cephalanthus occidentalls	Buttonbush	Shrub	Perennial, deciduous	Medium, 30 to 60 cm/yr		
Ceratophyllum demersum	Coontail	Submerged aquatic	Perennial	Rapid	Fragmentation	
Cyperus esculentus	Chufa	Emergent, herbaceous	Perennial, nonpersistent	Rapid	Rhizome	
Eichhornia crassipes	Water hyacinth	Nonrooted floating aquatic	Perennial, nonpersistent	Rapid	Stolons	
Hydrocotyle umbellata	Water-pennywort	Emergent to floating, herbaceous	Perennial, nonpersistent	Rapid	Stolons or rhizomes	
Iris versicolor	Blue flag	Emergent, herbaceous	Perennial, nonpersistent	Slow, <60 cm/yr	Bulb	0.15 to 0.45 m O.C.
Juncus effusus	Soft rush	Emergent, herbaceous	Perennial, persistent	Slow, <6 cm/yr	Rhizome	0.15 to 0.45 m O.C.
Lemna minor	Common duckweed	Nonrooted floating aquatic	Perennial, nonpersistent	Rapid	Fragmentation	
Nuphar luteum	Spatterdock	Rooted floating to emergent, herbaceous	Perennial, nonpersistent	Slow, <6 cm/yr	Rhizome	0.15 to 0.45 m O.C.
Nymphaea odorata	Fragrant water lily	Rooted, floating aquatic	Perennial, nonpersistent		Rhizome	
Nyssa sylvatica	Black gum	Tree	Perennial, deciduous	Slow	Suckers	

Plant species	Common name	Growth form	Persistence	Rate	Method	Spacing
Phragmites australis	Common reed	Emergent, herbaceous	Perennial, persistent	Rapid, >30 cm/yr	Rhizome	0.6 to 1.8 m O.C.
Pontederia cordata	Pickerelweed	Emergent, herbaceous	Perennial, nonpersistent	Moderate, 15 cm/yr	Rhizome	0.3 to 0.9 m O.C.
Populus deltoides	Eastern cottonwood	Tree	Perennial, deciduous	Fast, 1.2 to 1.5 m/yr		
Potamogeton nodosus	Long-leafed pond weed	Rooted sub-merged aquatic	Perennial, nonpersistent	Rapid	Rhizome	0.6 to 1.8 m O.C.
Quercus bicolor	Swamp white oak	Tree	Perennial, deciduous	Fast, 0.4 to 0.6 m/yr		
Rosa palustris	Swamp rose	Shrub	Perennial, deciduous			
Sagittaria latifolia	Duck potato	Emergent, herbaceous	Perennial, nonpersistent	Rapid, >30 cm/yr	Runners, tubers	0.6 to 1.8 m O.C.
Salix nigra	Black willow	Tree	Perennial, deciduous	Fast, 0.9 to 1.8 m/yr	Suckers	
Scirpus acutus	Hardstem bulrush	Emergent, herbaceous	Perennial, persistent	Rapid >30 cm/yr	Rhizome	0.9 to 1.8 m O.C.
Scirpus americanus	Olney's bulrush	Emergent, herbaceous	Perennial semi-persistent	Rapid, >30 cm/yr	Rhizome	0.6 to 1.8 m O.C.
Scirpus cyperinus	Wool grass	Emergent, herbaceous	Perennial, persistent	Moderate, 15 cm/yr	Rhizome	0.3 to 0.9 m O.C.
Scripus validus	Soft stem bulrush	Emergent, herbaceous	Perennial, persistent	Rapid, >30 cm/yr	Rhizome	0.6 to 1.8 m O.C.
Sparganium eurycarpum	Giant burreed	Emergent, herbaceous	Perennial, nonpersistent	Rapid, >30 cm/yr	Rhizome	0.6 to 1.8 m O.C.
Taxodium distichum	Bald cypress	Tree	Perennial, deciduous	Medium, 0.3 to 0.6 m/yr		
Typha angustifolia	Narrowleafed cattail	Emergent, herbaceous	Perennial, persistent	Rapid, >30 cm/yr	Rhizome	0.6 to 1.8 m O.C.
Typha latifolia	Broadleafed cattail	Emergent, herbaceous	Perennial, persistent	Rapid, >30 cm/yr	Rhizome	0.6 to 1.8 m O.C.

Continuation of same plant species list with additional characteristics

Plant species	Propagules	Habitat	Shade tolerance	Wildlife benefits	Water regime	Salinity tolerance
Acer negundo	Container	Forested wetlands	Full sun	Songbirds, waterbirds, small mammals	Irregular to regular inundation or saturation	Fresh water, resistant to salt water
Acer rubrum	Seed, whip, bare root	Fresh marsh, swamp, alluvial woods	Partial shade	Gamebirds, songbirds, browsers	Irregular to seasonally inundated or saturated	Fresh water, <0.5 ppt
Acorus calamus	Rhizome, bare root plant	Fresh to brackish marshes	Partial shade	Waterfowl, muskrat	Regular to permanent inundation <15 cm	Fresh to brackish water <10 ppt
Alnus serrulata	Container	Fresh marshes and swamps	Full sun	Songbirds, gamebirds, ducks, woodcock, blackbirds, beaver	Seasonal to regular inundation, up to 7 cm	Fresh water, <0.5 ppt
Carex spp.	Seed, bare root plant	Fresh marshes, swamps, lake edges	Full shade to full sun	Rails, sparrows, snipe, songbirds, ducks, moose	Irregular to permanent inundation, <15 cm	Fresh water, <0.5 ppt
Cephalanthus occidentalls	Seedling, bare root plant	Fresh marshes, swamps, edge of ponds	Full shade to full sun	Ducks, deer, rails, blackbirds, muskrat, beaver	Irregular to permanent inundation, up to 90 cm	Fresh water, tolerates infrequent salt water
Ceratophyllum demersum	Whole plant	Lakes, slow streams		Ducks, coots, geese, grebes, swans, marshbirds, muskrat	Regular to permanent inundation, 0.3 to 1.5 m	Fresh water, <0.05 ppt
Cyperus esculentus	Seed, tuber	Fresh marshes, wet meadows	Full sun	Waterfowl, songbirds, small mammals	Irregular to regular inundation, <0.3 m	Fresh water, <0.5 ppt
Eichhornia crassipes	Whole plant	Fresh water ponds and sluggish streams	Full sun	Coots, cover for invertebrates and fish	Permanent inundation	Fresh water, <0.5 ppt
Hydrocotyle umbellata	Bare root plant, whole plant	Shorelines, shallow marshes	Partial shade	Wildfowl, waterfowl	Regular to permanent inundation <30 cm	Fresh water, <0.5 ppt

Plant species	Propagules	Habitat	Shade tolerance	Wildlife benefits	Water regime	Salinity tolerance
Iris versicolor	Seed; bulb, bare root plant	Marshes, wet meadows, swamps	Partial shade	Muskrat, wildfowl, marshbirds	Regular to permanent inundation, <15 cm	Fresh to moderately brackish water
Juncus effusus	Seed, rhizome, bare root plants	Marshes, shrub swamps, wet meadows	Full sun	Wildfowl, marshbirds, songbirds, waterfowl	Regular to permanent inundation, <30 cm	Fresh water, <0.5 ppt
Lemna minor	Whole plant	Lakes and ponds	Partial shade	Ducks, gallinules, coots, rails, geese, beaver, muskrat, small mammals	Permanent inundation	Fresh water, <0.05 ppt
Nuphar luteum	Bare root plant	Marshes, swamps, ponds	Partial shade	Ducks, muskrat, fish	Regular to permanent inundation, up to 1.8 m	Fresh to infrequent brackish water
Nymphaea odorata	Bare root seedling	Ponds and lakes	Partial shade	Cranes, ducks, beaver, muskrat, moose	Permanent inundation, 0.3 to 0.9 m	Fresh water, <0.05 ppt
Nyssa sylvatica	Seed, bare root plant	Forested wetlands, swamps	Partial shade	Ducks, woodpeckers, songbirds, aquatic furbearers	Irregular to permanent inundation	Fresh to infrequent brackish water
Phragmites australis	Bare root plant	Fresh to brackish marshes, swamps	Full sun	Songbirds, marshbirds, shorebirds, aquatic furbearers	Seasonal to permanent inundation, up to water, up to 60 cm	Fresh to brackish water, up to 20 ppt
Pontederia cordata	Rhizome, bare root plant	Fresh to brackish marshes, edges of ponds	Partial shade	Ducks, muskrat, fish	Regular to permanent inundation up to 30 cm	Fresh to moderately brackish water, up to 3 ppt
Populus deltoides	Bare root plant container	Forested wetlands	Full sun	Gamebirds, songbirds, waterfowl, aquatic furbearers, browsers	Seasonal inundation or saturation	Fresh to infrequent brackish water

Plant species	Propagules	Habitat	Shade tolerance	Wildlife benefits	Water regime	Salinity tolerance
Potamogeton nodosus	Seed, bare root plant	Streams, lakes, ponds		Waterfowl, marshbirds, shorebirds, aquatic fur-bearers, moose, fish	Regular to permanent inundation, 0.3 to 1.8 m	Fresh water, <0.05 ppt
Quercus bicolor	Bare root plant, container	Forested wetlands	Partial shade	Waterfowl, marshbirds, shorebirds, gamebirds, songbirds, mammals	Irregular to seasonal inundation or saturation	Fresh to infre-quent brackish water
Rosa palustris	Container	Fresh marshes, shrub swamps	Full sun	Songbirds, gamebirds	Irregular to regular soil saturation	Fresh water, <0.5 ppt
Sagittaria latifolia	Tuber, bare root plant	Fresh marshes, swamps, edge of ponds	Partial shade	Ducks, swans, rails, muskrat, beaver	Regular to permanent inundation, up to 60 cm	Fresh water, <0.5 ppt
Salix nigra	Bare root, container	Fresh marshes, swamps	Full sun	Gamebirds, ducks, song-birds, wood-peckers, aqua-tic mammals	Irregular to permanent inundation	Fresh water, <0.5 ppt
Scirpus acutus	Seed, rhizome	Fresh to brackish marshes	Full sun	Ducks, geese, swans, cranes, shorebirds, rails, snipe, muskrat, fish	Regular to permanent, up to 90 cm	Fresh to brack-ish water
Scirpus americanus	Rhizome, bare root plant	Brackish and alkali marshes	Full sun	Ducks, geese, swans, cranes, shorebirds, rails, snipe, muskrat, fish	Regular to permanent, up to 30 cm	Fresh to brack-ish water, up to 15 ppt
Scirpus cyperinus	Rhizome, bare root plant	Fresh marshes, wet meadows, sloughs, swamps	Full sun	Ducks, geese, swans, cranes, shorebirds, rails, snipe, muskrat, fish	Irregular to seasonal inundation	Fresh water, <0.5 ppt

Plant species	Propagules	Habitat	Shade tolerance	Wildlife benefits	Water regime	Salinity tolerance
Scirpus validus	Rhizome, bare root plant	Fresh and brackish marshes	Full sun	Ducks, geese, swans, cranes, shorebirds, rails, snipe, muskrat, fish	Regular to permanent inundation, up to 30 cm	Fresh to brackish water, up to 5 ppt
Sparganium eurycarpum	Seed, rhizome, bare root plant	Marshes, swamps	Partial shade	Ducks, swan, geese, beaver, muskrat	Regular to permanent inundation up to 30 cm	Fresh water, <0.5 ppt
Taxodium distichum	Seed, bare root	Fresh water swamps, pond and lake margins	Partial shade	Perching and nesting site for birds	Irregular to permanent inundation	Fresh water, <0.5 ppt
Typha angustifolia	Rhizome, bare root	Fresh and brackish marshes, pond edges	Full sun	Geese, ducks, muskrat, beaver, blackbirds, fish	Irregular to permanent inundation, up to 30 cm	Fresh to brackish water, up to 15 ppm
Typha latifolia	Rhizome, bare root plant	Fresh marshes, pond margins	Full sun	Geese, ducks, muskrat, beaver, blackbirds, fish	Irregular to permanent inundation, up to 30 cm	Fresh water, <0.5 ppt