A HANDBOOK OF CONSTRUCTED WETLANDS

a guide to creating wetlands for:

AGRICULTURAL WASTEWATER
DOMESTIC WASTEWATER
COAL MINE DRAINAGE
STORMWATER

in the Mid-Atlantic Region

Volume 3

AGRICULTURAL WASTEWATER

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

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CHAPTER 1
INTRODUCTION

This volume focuses on the use of constructed wetlands to treat agricultural wastewater. It is to be used in combination with Volume 1: General Considerations, which provides information on wetland hydrology, soils, and vegetation, and on the design, construction, operation, and maintenance of constructed wetland systems.

Constructed wetlands can provide an inexpensive and easily operated means of removing organic matter, particulates, nutrients, and bacteria from agricultural wastewater. Agricultural wastewaters suitable for wetland treatment include milkhouse wastewaters, runoff from concentrated livestock areas, and effluents from settling tanks and manure treatment lagoons.

Interest in using constructed wetlands to treat agricultural wastewaters has been prompted by the success of constructed wetlands in removing organic matter, particulates, and nutrients from municipal wastewaters. However, the use of constructed wetlands in agriculture is a fairly recent development and the number of systems that have been installed is still small. While the data show that properly designed wetlands can be effective in treating agricultural wastewater, much is not yet understood and many of the relationships between design and performance have not been clearly established. The use of constructed wetlands in agriculture will be modified and refined as more systems are installed and monitoring data are gathered over longer periods of time. The guidance presented here should be considered as today's "state of the art" and will likely be modified as our understanding of these systems grows.

As with other agricultural waste management practices, constructed wetlands are one component of an overall agricultural waste management system (AWMS). This Handbook discusses the contributions that constructed wetlands can make to an AWMS, the performance that can reasonably be expected, and the factors that are important in the design of effective constructed wetlands. Step-by-step procedures in designing constructed wetlands are given.

This volume incorporates the guidance presented in the Soil Conservation Service (SCS, now the Natural Resources Conservation Service) *Constructed Wetlands for Agricultural Wastewater Treatment Technical Requirements* (1991), which is an important reference for those interested in using constructed wetlands in agriculture.

CHAPTER 2
USING CONSTRUCTED WETLANDS IN AGRICULTURE

CONTAMINANT REMOVAL PROCESSES

The most important removal mechanisms in agricultural constructed wetlands are physical sedimentation and filtration, and biological assimilation, breakdown, and transformation (table 1). The suspended solids that remain in the effluent from pretreatment unit are removed in the wetland by sedimentation and filtration. These physical processes also remove a significant portion of other wastewater constituents, such as biochemical oxygen demand (BOD), nutrients, and pathogens (Brix 1993). Soluble organic compounds are, for the most part, degraded by microbes, especially bacteria, that are attached to the surfaces of plants, litter, and the substrate.

ADVANTAGES AND LIMITATIONS OF CONSTRUCTED WETLANDS

Constructed wetland treatment of agricultural wastewater offers a number of advantages (table 2),

Table 1. Removal mechanisms in constructed wetlands (after Brix 1993).

Wastewater Constituent	Removal Mechanisms
Biochemical oxygen demand	Microbial degradation (aerobic and anaerobic)
	Sedimentation (accumulation of organic matter/sludge on sediment surfaces)
Suspended solids	Sedimentation/filtration
Nitrogen	Chemical ammonification followed by microbial nitrification and denitrification
	Plant uptake
	Volatilization of ammonia
Phosphorus	Soil sorption (adsorption-precipitation reactions with aluminum, iron, calcium, and clay minerals in the soil)
	Plant uptake
Pathogens	Sedimentation/filtration
	Natural die-off

Table 2. Advantages and limitations of constructed wetland treatment.

Advantages	Limitations
• are capable of providing a high level of treatment	• are affected by season and weather, which may reduce treatment reliability
• can reduce or eliminate odors	• are sensitive to high ammonia levels
• are inexpensive to operate	• may hold potential for mosquitoes and other insect pests
• are largely self-maintaining	• require a continuous supply of water
• are able to handle variable wastewater loadings	• require dedicated, single land use
• reduce the amount of area needed for land application	• may be more expensive to construct than other treatment options

including odor control and simplicity of operation. Constructed wetland treatment is constrained by a number of limitations, including variability in treatment effectiveness and the sensitivity of wetland plants to high ammonia concentrations. The advantages and limitations of a constructed wetland as an alternative to other treatment options must be understood and weighed before deciding to install a constructed wetland.

CREATING EFFECTIVE CONSTRUCTED WETLANDS

Suggestions for creating an effective constructed wetland are given in table 3. Since the objective of using a constructed wetland is to simplify the handling of wastewater, the system should be made as easy as possible to operate while ensuring reliable treatment. Building a slightly larger system may be more expensive to construct but may be less costly and more reliable to operate than a smaller system. Attention to several factors will help to ensure successful wetland treatment:

- Adequate pretreatment. Pollutant loads in agricultural wastewaters often greatly exceed the ability of a wetland to treat or assimilate them. A wetland can be severely damaged by a wastewater that is too concentrated, for instance, one that contains high levels of ammonia. Pretreatment to lower pollutant loads is essential to avoid overloading the wetland.
- Adequate retention time. A wetland treats wastewater through a number of biological (largely microbial), physical, and chemical processes. The water must remain in the wetland long enough for biological and chemical transformations to take place and for

Table 3. Guidelines for creating constructed wetlands.

Know what you are dealing with	Sample the wastewater Know what pretreatment will accomplish
Size the wetland generously	Too small a wetland cannot perform well
Wetlands must have water	Know the water budget Provide a supplemental source of clean water
Give the plants a chance	Allow time for establishment Avoid shock loading Keep ammonia levels to 100 mg/L or less
Don't overload the wetland	Application rates must not exceed treatment rates
Don't kill the wetland	Keep raw milk out of the wetland Keep herbicides out of the wetland
Effluent disposal must be addressed	Use other recognized practices
Keep an eye on what is happening	Monitoring is important
Get interdisciplinary help	Environmental engineer Water quality specialist Plant materials specialist/biologist/extension agent State agencies

sedimentation and deposition to occur. The wetland must be built large enough to provide the necessary retention time.

- Supplemental water. If a constructed wetland is to remain healthy, it must remain relatively wet. Wetlands are generally tolerant of fluctuating flows, but they cannot withstand complete drying. For this reason, either a slow release of wastewater must be assured or a supplemental source of water must be provided. Supplemental water can be used to dilute the wastewater to acceptable levels and also to assure that the wetland stays wet. Enough water should be supplied to the wetland to maintain a slow flow of water, since stagnant water can lead to problems with odors and mosquitoes.
- Proper management. Constructed wetlands are "high management, low maintenance" systems. They must be actively managed if they are to perform well. "Management" means watching the wetland for signs of stress or disease and adjusting water levels or input streams accordingly. While wetlands are low maintenance systems, they are not maintenance-free. For instance, the pretreatment unit must be cleaned periodically to keep excessive solids from entering the wetland, and valves and piping must be checked to detect and correct blockages or leaks.

TYPES OF CONSTRUCTED WETLANDS

Most wetlands used in agriculture are surface flow (SF) wetlands. The advantages of SF wetlands are that their design and construction are straightforward. Operation and maintenance are simple. Because the water surface is unconstrained, SF wetlands are able to accept wide variations in flow. SF wetlands can provide excellent removal of 5-day biochemical oxygen demand (BOD_5) and total suspended solids (TSS). Good removal of ammonia and total nitrogen has been achieved at some wetlands. SF wetlands are discussed in Chapter 4.

In subsurface flow (SSF) wetlands, the water level must remain below the surface of the substrate if the wetland is to perform well. The design and construction of SSF wetlands are therefore more complicated than for SF wetlands and SSF wetlands must be managed and monitored much more closely. There have been problems with unintended surface flow and apparent plugging. Because of the hydraulic constraints imposed by the media, SSF wetlands are best suited to relatively uniform flows. Their use in agriculture has thus been limited. SSF wetlands may be appropriate for field drain discharges and research on such systems is being conducted.

SSF systems are discussed in Chapter 5.

WASTEWATER CHARACTERISTICS

To design the wetland correctly, an accurate assessment of contaminant loadings is needed (loading = contaminant concentration x wastewater volume). To calculate loadings, data are needed on the average water quality, the maximum concentrations, and the largest and smallest volumes that may occur. Loadings may vary throughout the year as the volumes of water change in response to climatic factors, such as rainfall and evaporation. Maximum concentrations will probably occur in the late summer and fall, when water losses due to evapotranspiration are greatest. The highest flows can be expected during the wet season, but pollutant concentrations may be lower at this time because of dilution. The design should be based on the highest pollutant loadings.

WATER QUALITY

The characteristics of agricultural wastewater vary, depending on the specifics of the agricultural operation, and should be determined by laboratory analysis before the wetland is designed. The Soil

Conservation Service (SCS, now the Natural Resources Conservation Service) recommends the following analyses for agricultural wastewater (SCS 1991):

- 5-day biochemical oxygen demand (BOD_5)
- total solids (TS)
- total Kjeldahl nitrogen (TKN)
- nitrate nitrogen (NO_3-N)
- ammonia nitrogen (NH_3 + NH_4-N)
- total phosphorus (TP).

The design of the wetland is usually based on the removal of BOD (usually measured as 5-day biochemical oxygen demand, BOD_5) or nitrogen (measured as total Kjeldahl nitrogen or nitrate nitrogen). Concentrations of ammonia (NH_3 + NH_4-N, un-ionized ammonia + the ammonium ion) should be evaluated because of the toxicity of ammonia to wetland plants.

Additional analyses may be needed. For instance, if high salinities could occur, chloride concentrations should be measured to determine the salinities that the vegetation will be exposed to; salinities in the brackish range will suggest that salt-tolerant vegetation should be planted. The likelihood of toxic compounds, and high or low pHs that could affect the biological components of the wetland should be considered.

Water Quantity

An accurate estimate of the volume of wastewater is needed, including the expected average, maximum, and minimum wastewater flows. An accurate figure for the volume of water to be treated must be determined: too small a wetland will perform poorly; a large wetland may require supplemental water to maintain the wetland during the dry season. The maximum expected flow must be determined. If the maximum expected flow is larger than the capacity of the wetland, a bypass will be required. The minimum expected flow should be calculated to determine the volume of supplemental clean water that may be needed.

PRETREATMENT

Raw agricultural wastewaters are characterized by very high concentrations of BOD_5, nutrients, and total and dissolved solids. To avoid overloading wetland removal capabilities, raw wastewaters must be pretreated to lower the concentrations of these contaminants. Pretreatment is also necessary to lower nutrient and organic loads (particularly ammonia) to avoid damaging the wetland vegetation. Pretreatment to lower total organic loading also helps to control mosquito populations (Wieder et al. 1989). Pretreatment can be made through settling tanks and basins, flotation tanks, filters, or mechanical separators, either singly or in combination. The Agricultural Waste Management Field Handbook (SCS 1992) discusses various pretreatment options.

In the northeastern United States, percent removals in BOD_5 by settling tanks are generally around 70%. To protect the vegetation, SCS (1991) suggests a target concentration of 100 mg/L ammonia for the effluent from the pretreatment unit. However, Reaves et al. (1995) found that while concentrations of 200 - 300 mg/L ammonia damaged the growth of young cattail shoots in a wetland used to treat swine effluent, mature cattails did not seem to be affected. Reaves et al. (1995) theorize that the ammonia may be present as the non-toxic ammonium ion (NH_4^+) rather than the toxic ammonia ion (NH_3).

Pretreatment must remove solids. Most settleable, floating, and non-biodegradable solids, such as plastics and grease, must be removed before the water enters the wetland or the wetland will eventually clog. Pretreatment to remove solids also avoids potential clogging of pipelines, gates, and valves. Since bacteria and viruses adsorb on solids, pretreatment to decrease solids also decreases the numbers of bacteria and viruses (Ives 1988). SCS (1991) suggests 1,500 mg/L total solids or less as a target concentration for the effluent from the pretreatment unit.

Fats are a particular problem since they float on the surface of the water, causing a scum that blocks gas transport and rapidly depletes dissolved oxygen. Raw milk can suffocate a wetland and must be kept out of the wetland.

An organic filter (a bed of chipped mixed wood bark) is being tested as a means of reducing odors and ammonia concentrations at a veal operation (Murphy et al. 1993). The effluent from the settling tanks passes through the filter by subsurface flow before entering the wetland. The bed has completely eliminated odors; ammonia removals have been variable.

In addition to pretreatment, dilution may be necessary for some wastewaters. The wetland system can be designed to recycle the wetland effluent for use in diluting the effluent from the pretreatment unit.

DISCHARGE OPTIONS

There are several options for the wetland effluent:

- storage for later land application
- discharge to an infiltration area
- recycle through the wetland.

Where possible, the effluent should be recycled. Recyling the treated effluent from the wetland is an efficient way to dilute influent BOD_5 and suspended solids. Recycling decreases the potential for odors and may possibly increase dissolved oxygen concentrations, which in turn may enhance nitrification. Recycling is also an efficient way to maintain adequate flows during low-flow periods.

The disadvantages of recycling are the increased construction costs and increased operation (pumping) costs. Also, recyling may slowly increase salinities as evapotranspiration removes water from the system.

CHAPTER 3
PERFORMANCE EXPECTATIONS

INTRODUCTION

Data on agricultural systems are limited, both in the number of systems that have been built and in the length of time the systems have been operating. However, a number of constructed wetland systems are being used to treat domestic wastewaters, which contain a array of contaminants similar to those in agricultural wastewater. Information from domestic systems is thus useful in assessing the potential of constructed wetlands to treat agricultural wastewater.

BIOCHEMICAL OXYGEN DEMAND AND TOTAL SUSPENDED SOLIDS

Wetlands provide a number of mechanisms for removing BOD_5 and TSS, and constructed wetlands are extremely efficient at removing these contaminants. At seven agricultural systems that have recently begun operating, removals range from about 60% to more than 90% (table 4). In a survey of 324 municipal, industrial, stormwater, and other constructed wetlands, Knight et al.

Table 4. Summary of agricultural constructed wetland operational data

	BOD_5 (mg/L)			TSS (mg/L)			NH_3-N (mg/L)			TN(mg/L)			TP(mg/L)		
	In	Out	%	In	Out	%	In	Out	%	In	Out	%	In	Out	%
Dairy[a]	37	13	65	137	44	68	6.5	0.4	93	-	-	-	13.5	3.3	76
	36	9	75	109	56	49	6.1	0.3	95	-	-	-	14.4	3.8	74
	37	11	70	125	47	62	7.5	1.2	84	-	-	-	14.2	5.7	60
Dairy[b]	1,343	375	68	700	281	65	243	68	70	654	201	56	56	24	58
	1,688	339	81	7,216	151	89	208	110	51	476	215	57	75	22	78
	1,998	397	62	1,338	558	42	343	90	50	890	275	36	62	23	49
Dairy[c]	354	138	61	282	75	73	64	29	54	92	38	57	14	5	66
Swine[d]	64	6	91	105	9	91	54.7	3.5	94	70	6	91	25.8	6.2	76
Swine[e]	45	28	38	118	17	86	94	23	76	104	41	61	66	30	55
	45	9	80	118	10	92	94	3	97	104	6	94	66	23	65
	45	9	80	118	9	92	94	2	98	104	5	95	66	15	77
Swine[f]	47	20	56	94	31	67	112	36	68	-	-	-	28	18	36
	45	24	47	88	36	59	112	41	63	-	-	-	27	16	41
Chicken manure[g]	1,320	230	83	1,060	155	85	-	-	-	295	<95	68	22	<4	>80
	1,550	190	88	1,300	130	90	-	-	-	320	64	80	25	5	80
Field drain effluent[h]	-	-	-	-	-	-	0.3	0.3	0	23	21	6	0.02	0.02	0

%: percent removal

a surface flow, milkhouse wash water + runoff + rainfall, Mississippi, 2 years of data (Cooper et al. 1993)

b surface flow, barn washwater + yard runoff, Indiana, 1 year of data (arcsine means) (Reaves et al. 1994)

c surface flow, milking parlor washwater + yard runoff + rainfall, Oregon, 6 months of data (Skarda et al. 1994)

d surface flow, effluent diluted with stormwater pond effluent, Alabama, 1 year of data (Hammer et al. 1993)

e surface flow, lagoon effluent, flow rates of 2610 gpd/1094 gpd/540 gpd (lines 1-3), Alabama, 3 months of data (McCaskey et al. 1994)

f surface flow, lagoon effluent, marsh-pond-marsh system, Mississippi, 16 months of data (Cathcart, Hammer, and Triyono 1994)

g subsurface flow, dilute chicken manure, Czechoslovakia, 1 year of data (Vymazal 1993)

h subsurface flow, cropland tile drain effluent, Pennsylvania, 4 years of data (Taylor et al. in preparation)

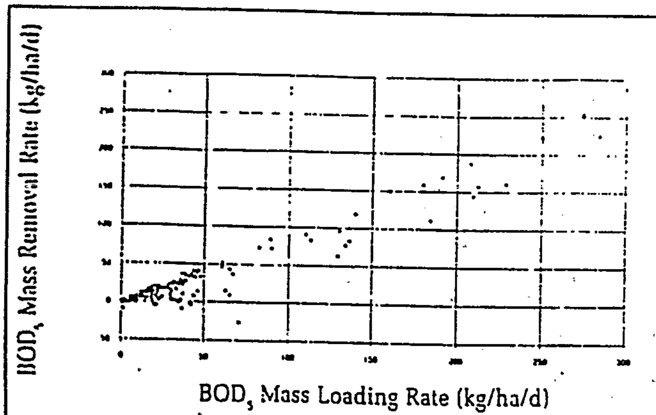

Figure 1. BOD_5 mass loading and removal rates in wetland treatment systems (from Knight et al. 1993).

(1993) found that BOD_5 mass removal efficiencies were generally 70% or more at mass loading rates up to 250 lb/ac/day (280 kg/ha/day), which is considerably higher than the 65 lb/ac/day recommended by SCS (1992) as the maximum BOD_5 loading rate for agricultural wetlands. A linear regression of the 324 data records used to examine the predictability of BOD_5 outflow concentration as a function of BOD_5 inflow concentration and hydraulic loading produced the following (figure 1) (Knight et al. 1993):

$$BODOUT = 0.097*HLR + 0.192*BODIN$$
$$R^2 = 0.72$$

where

BODOUT = BOD_5 outflow concentration, mg/L
BODIN = BOD_5 inflow concentration, mg/L
HLR = hydraulic loading rate, cm/day.

While average annual removal rates were usually high, rates sometimes varied considerably on a monthly or seasonal basis (Knight et al. 1993).

In wetlands, BOD is produced within the system by the decomposition of algae and fallen plant litter. As a result, wetland systems do not completely remove BOD and a residual BOD_5 of 5 to 7 mg/L is often present in wetland effluent (EPA 1993). This internal production of BOD decreases removal efficiencies at very low inflow concentrations.

TSS is removed primarily by sedimentation and filtration, and removal is enhanced as the density of surfaces within the wetland increases. Cooper et al. (1993) found that TSS removals increased as plant litter accumulated.

To maximize the removal of BOD_5 and TSS, the growth of plants (particularly underground tissues) and the accumulation of litter should be encouraged. Plants and plant litter provide organic carbon and attachment sites for microbial growth, and promote filtration and sedimentation. Because of the importance of microbial processes in removing BOD_5, adequate residence time must be provided. The SCS (1991) recommends a hydraulic residence time of at least 12 days.

NITROGEN

In contrast to the simplicity of BOD and TSS removal, the chemistry of nitrogen removal is complex (figure 2). Nitrogen occurs in a number of forms, including organic and inorganic compounds, and nitrogen gas. In wetlands, the important forms include nitrogen gas (N_2), nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3), and ammonium (NH_4^+).

In wetlands, the removal of nitrogen involves a series of reactions (Mitsch and Gosselink 1986). Decomposition and mineralization processes convert a significant part of organic nitrogen to ammonia. Ammonia is oxidized to nitrate by nitrifying bacteria in aerobic zones (nitrification) and nitrates are converted to nitrogen gas by denitrifying bacteria in anoxic zones (denitrification); the gas is released to the atmosphere. The sequence is:

mineralization:		
organic nitrogen	-> ammonia nitrogen	aerobic or anaerobic reaction
nitrification:		
ammonia nitrogen	-> nitrate nitrogen	aerobic reaction
denitrification:		
nitrate nitrogen	-> nitrogen gas	anaerobic reaction, requires a carbon source as food for the bacteria

Since nitrification is an aerobic process, rates are controlled by the availability of dissolved oxygen to the nitrifying bacteria, and by temperature. The oxygen required for nitrification can be delivered either directly from the atmosphere through the water or sediment surface, from photosynthesis by algae, or by leakage from plant roots. Denitrification is typically very rapid and the loss of nitrogen gas to the atmosphere represents a limitless sink. The decaying plant litter in wetlands may provide anaerobic sites for denitrification (Crumpton et al. 1993).

Some nitrogen is also taken up by plants and incorporated into plant tissue, but this removal pathway is of limited importance in the eastern United States because the above-ground parts of most wetland plants die back yearly and because below-ground tissue increases only very slowly (Brix 1993). Nitrogen is generated in wetlands through a natural process (nitrogen fixation) in which some plants convert atmospheric nitrogen into the organic form. Most wetland plants are able to fix nitrogen and natural background concentrations of total nitrogen (TN) are generally in the range of 0.5 to 3 mg/L.

In wetlands built to treat domestic wastewaters, TN removal has been highly correlated to loading rates of less than 9 lb/ac/day (10 kg/ha/day), with removal efficiencies typically between 72% and 95% (figure 3)(Knight et al. 1993). At loading rates between 9 and 80 lb/ac/day, total nitrogen removal efficiency varied widely, with some systems showing high values and others much lower values. EPA (1988) reported nitrogen removals of 60% to 86% at hydraulic residence times of 5 to 7 days. The recommended loading rate for agricultural wetlands is 9 lb/ac/day or less.

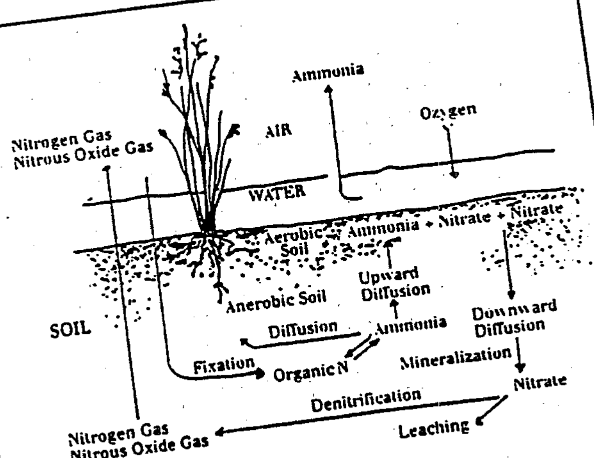

Figure 2. Nitrogen transformations (after Gambrel and Patrick 1978, in Mitsch and Gosselink 1986).

For the agricultural wetlands listed in table 4, total nitrogen removal efficiencies for dairy and swine effluents ranged from 36% to 95%. Better removals from swine effluent occurred at lower flow rates (McCaskey et al. 1994).

At the Iselin, Pennsylvania, domestic wastewater constructed wetland, ammonia removal averaged 77%, ranging from 93% in the summer to 54% in the winter (Conway and Murtha 1989). This system comprised an aeration cell (residence time 3 days), a cattail SF cell, a pond with plants to remove nutrients and fish to remove the plants (residence time 22 days), and a meadow planted with reed canary grass. The system thus provided ample opportunities for aeration.

Many constructed wetlands for municipal wastewater treatment are unable to meet their discharge limits for ammonia. Reed and Brown (1992) believe that this may be due to the insufficient availability of oxygen for the nitrifying organisms. In SF wetlands, the water may be too deep and the vegetation too dense for wind and turbulence of the water surface to provide significant aeration. One attempt to correct this problem combines shallow overland flow with a SF wetland. Hammer (1992) suggests a marsh-pond-marsh sequence within a single cell to improve nitrogen removal: the water passes through a SF wetland to convert organic nitrogen to ammonia, then through a pond (a deeper, open-water area) for the nitrification of ammonia to nitrate and subsequent denitrification to nitrogen gas, and then though another SF wetland to complete the removal of BOD_5 and TSS and the denitrification of nitrate. Cathcart et al. (1994) found that dissolved oxygen levels were higher during the day in the open water pond due to production of oxygen by algae, resulting in consistent ammonia removals which averaged 68% and 63% (Table 4). However, the algae were thought to contribute to increased BOD_5 levels in the effluent.

Hunt et al. (1994) found that nitrification (and therefore ammonia removal) was curtailed during the warmer months when oxygen demand was high and diffusion of oxygen was low. They suggest adding an oxidative step, such as overland flow, after the wetland to increase ammonia removal.

PHOSPHORUS

In wetlands, phosphorus is a highly mobile element that is involved in many biological and soil/water interchanges. Dissolved phosphorus can be present in organic or inorganic forms and is transferred readily between the two forms. It has been generally assumed that microbes, algae, and vascular plants may cycle phosphorus seasonally, with uptake during the growing season and release to the water column on death and decay. However, data on the annual recycling of phosphorus are limited. Harvesting the above-ground portions of vascular plants at the end of the growing was shown to be an ineffective means of removing phosphorus because much of the phosphorus had been gradually translocated to the roots and rhizomes before then (Mitsch and Gosselink 1986).

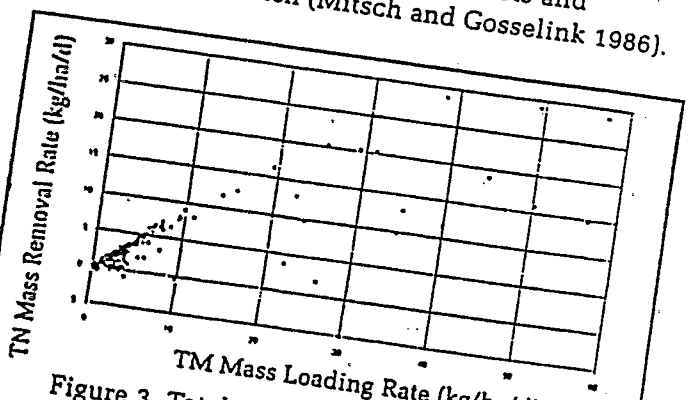

Figure 3. Total nitrogen mass loading and removal rates in wetland treatment systems (from Knight et al. 1993).

The long-term removal of phosphorus by constructed wetlands is limited. The soil is the major sink for phosphorus in most wetlands. Phosphorus may be buried in organic form in peats or chemically adsorbed in complexed forms with aluminum, iron, and calcium (Richardson and Craft 1993). Soil adsorption can result in a significant removal of dissolved phosphorus for a while after system startup, but removal then decreases as adsorption sites become filled. The length of the removal period depends on the chemical adsorption capacity of the sediments and can be estimated through laboratory analyses. Wetland soils have markedly different phosphorus adsorption capacities.

To increase phosphorus retention, a dense growth of plants should be encouraged to maximize the buildup of litter and sediment, and to promote precipitation. If phosphorus removal is a major goal, periodic replacement of the substrate to maintain high removal efficiencies is an option. In this case, the substrate and accumulated litter must be removed, a new substrate provided, and the wetland replanted.

PATHOGENS

Pathogens are removed by die-off, filtration, predation, and adsorption on solids. Some wetland plants excrete antibiotics which further aid in the removal of pathogens. In general, most pathogenic microorganisms are highly host-specific and do not survive for long apart from the host. Because viruses are charged particles, viruses readily become attached to solids and other particles (Wolverton 1989).

Constructed wetlands provide high percentage removals of pathogens: wetlands remove bacteria and viruses from domestic wastewaters at efficiencies of 90% to 99% at hydraulic retention times a short as 3 to 6 days. Removal of bacteria and viruses by wetlands is promoted by densely vegetated cells and by retention times longer than 3 days (Ives 1988).

Despite the high removal rates, the effluent from a constructed wetland may still contain enough organisms to make the water unsuitable for livestock. If pathogens are a concern, the water should be passed through a vegetated filter strip after leaving the wetland.

TOXICS

Toxic compounds (pesticides, herbicides, and heavy metals) are of concern in wetland treatment because of their potential effects on the microbes and plants of the wetland. Pesticides, herbicides, and heavy metals are either oxidized in the water column and then precipitated in the sediments (Water Pollution Control Federation 1990) or are adsorbed and complexed with organic material in the wetland sediments (Brix 1993). Toxicity to the plants and microbes must be controlled to protect the assimilative capacity of the wetland. If toxic compounds are a potential problem, the wastewater should be analyzed to determine concentrations before the wetland is designed.

CHAPTER 4
SURFACE FLOW WETLANDS

WETLAND DESIGN

Guidelines to designing a SF constructed wetland are given in table 5. The design assumes that the wastewater has been pretreated to reduce BOD_5 by 70%, TSS to less than 1,500 mg/L, and ammonia to less than 100 mg/L.

CONFIGURATION

The configuration should take advantage of the natural topography of the site to minimize excavation and grading costs. The configuration should allow water to move through the wetland by gravity. The wetland should not be placed where excess solids could be washed into the wetland; for instance, sites next to solids settling pads should be avoided. While treatment wetlands are often designed as rectangles, wetlands can be built as semi-circular or irregular shapes to fit the topography of the site. Using curved shapes also eliminates right-angled corners, which tend to be "dead water" areas. If a shape other than a rectangle is used, the widest portion should be located at the inlet end to facilitate equal flow distribution.

For large wetlands, dividing the wetland into side-by-side cells should be considered. Dividing a wide wetland into parallel cells lessens the likelihood of preferential flow paths and short-circuiting and promotes the contact of the wastewater with the surfaces in the wetland. It also facilitates maintenance since one set of cells can be taken out of operation temporarily.

If the removal of nitrogen and ammonia is a major objective, including a deeper (2 - 3 ft) open water pond in the middle of a longer wetland cell should be considered to increase nitrification and denitrification.

Table 5. Design summary for surface flow wetlands.

Pretreatment	Reduction of BOD_5 by 70% Reduction of solids to <1,500 mg/L Reduction of ammonia to <100 mg/L
Configuration	Fit the wetland to the site Divide large wetlands into side-by-side cells
Flow	By gravity, as much as possible
Bottom slopes	Side-to-side elevations: level Inlet to outlet slopes: almost flat (0.5 - 1.0%)
Water depth	3 - 8 inches, depending on the plants selected 18 inches maximum
Vegetation	Complete coverage is more important than the species used Use at least two or three different species
Construction	Wetland must be sealed to limit infiltration and exfiltration Water table must be below or excluded from the wetland

Water Depth

The design should plan for 3 to 8 inches of surface water, with a maximum of 18 inches. Deeper water may be advisable in winter to accommodate the slower reaction rates during cold weather and to guard against freezing. The wetland may have to be divided lengthwise into a series of cells to prevent the water in any of the cells from being deeper than desired. Each cell will then discharge to a downstream cell of the same width. The maximum length of each cell is based on the slope of the bottom of the cell (which should not exceed 0.5 to 1.0%) and the water depth suitable for the wetland vegetation (which is generally 18 inches or less). The number and length of the subdivisions will depend on the length of the cells and the slope of the bottom.

The bottom of the cells should be flat from side to side to assure an even distribution of water across the cells and to prevent channeling.

SIZING

Procedures for sizing SF wetlands for the removal of BOD_5, TSS, and nitrogen are still preliminary. It has been widely presumed that simple first order chemical reaction rates apply for pollutant removal and that constructed wetlands roughly follow plug flow in their internal hydrology. However, several recent studies have shown that the movement of water through constructed wetlands is considerably more complex than that described by standard flow equations (Kadlec et al. 1993, Kadlec 1994). The flow through a wetland is related to the morphology of the cell, the pattern of vegetation density, and the balance between evapotranspiration and precipitation. Constructed wetlands exhibit mixing characteristics intermediate between plug flow and well-mixed, flows are typically in the transition zone between laminar and turbulent, and hydrologic conditions change continuously with changes in the weather and the seasons. Factors such as obstructions to flow, the development of channeling, recirculation patterns, and the presence of stagnant areas cause further deviations from calculated theoretical flows. Contact times are not often as great as the theoretical residence time calculated from the wetland empty volume and the volumetric flow rate. As a final complicating factor, the chemistry of wetlands is complex, involving interrelated biological reactions and mass transfers. These factors and the lack of good information on factors such as reaction rate constants have probably led to many systems being underdesigned.

Agricultural wetland systems are usually sized to remove the necessary amount of BOD_5. The SCS (1992) uses two methods to determine the size of a constructed wetland for a specific site: the presumptive method and the field test method.

The presumptive method is used when the pretreatment system has not yet been installed and the concentration of BOD_5 in the pretreatment unit can only be estimated. The presumptive method first calculates a surface area and then determines the resulting hydraulic residence time, adjusting the size as necessary to achieve the required residence times.

The field test method uses known, measured BOD_5 concentrations in the effluent from the pretreatment unit to calculate hydraulic residence times, from which the required surface area is then calculated.

Removal efficiencies for TSS are similar to those for BOD_5 and design for BOD_5 removal should achieve similar TSS removal.

For wetlands designed to remove ammonia as well as BOD_5, the size of the wetland should be based on the removal of the ammonia. Since ammonia removal is a less efficient process than BOD_5 removal, ammonia removal requires a larger wetland area than does BOD_5 removal.

Presumptive Method for BOD_5

This method assumes that a certain amount of BOD_5 is present in the wastewater and that a certain amount is removed by the pretreatment system. It then uses the remaining BOD_5 load with a standard wetland areal loading rate to determine the surface area needed for adequate treatment.

1. Determine the production of BOD_5 per day: Livestock production of BOD_5 is as follows:

	Average weight (lb)	production (lb) 1000 lb animal unit (AU) per day
Dairy cows	1300	1.6
Beef cattle	750	1.4
Swine	200	2.1
Poultry - layers	4	3.7
Poultry - broilers	2.2	5.1

   BOD_5 = BOD_5/1000 lb AU x number of animals x average weight/1000 lb

2. Add 10% BOD_5 to account for that in waste hay and feed:
   Adjusted BOD_5 = BOD_5 x 1.1

3. Determine BOD_5 remaining after pretreatment, if known.
   A well-managed settling/flotation tank for milkhouse wastewater will remove 70% of BOD_5. Use a removal factor of 0.30 (70% removal):
   BOD_5 remaining in tank effluent = adjusted BOD_5 x 0.30
   If using an anaerobic lagoon, use a rate of 40% rate (60% removal):
   BOD_5 remaining in lagoon effluent = adjusted BOD_5 x 0.40

4. Determine the water surface area (SA) for the constructed wetland:

   SA = BOD_5 loading / recommended areal BOD_5 loading rate
   SCS recommends an areal BOD_5 loading rate of 65 lb BOD_5/ac/day. It is known that treatment, and therefore areal loading rate, are affected by climate but no research or field data are available that can be used to quantify the influence of different climate conditions. A standard value is therefore used.

5. Determine the overall dimensions. The optimal length-to-width ratio has not yet been determined. The SCS (1992) recommends a ratio of 3:1 to 4:1. For a length-to-width ratio of 3:1:

   W = width of constructed wetland
   L = length = 3W

   Then SA = 3W x W = $3W^2$

6. Determine the hydraulic residence time (t) in days. Data needed are average water depth (D), porosity (P), and daily flow rate (Q).

$$t = SA \times D \times P / Q \tag{4.1}$$

where: t = hydraulic residence time, days
SA = surface area of constructed wetland, ft^2 (length x width)
D = average water depth in constructed wetland, ft
Q = average daily flow rate, ft^3/day
P = porosity, percent as a decimal.

The Q value is the average flow in the bed, calculated from flow through the bed plus gains and losses from precipitation and evapotranspiration. Published values are usually available for precipitation and evapotranspiration for local conditions. Large rainfall and snowmelt volumes can greatly affect Q and must be considered in the design; some constructed wetlands have failed because high flows were not factored into the design.

The porosity (P) is the ratio of the volume occupied by water to the volume occupied by plants and water combined. The following porosity values have been determined:

cattails (*Typha* spp.)	0.95	(SCS 1992)
bulrush (*Scirpus validus*)	0.86	(Watson and Hobson 1989)
woolgrass (*S. cyperinus*)	0.86	(Watson and Hobson 1989)
common reed (*Phragmites*)	0.98	(Watson and Hobson 1989)
rushes (*Juncus* spp.)	0.95	(Watson and Hobson 1989).

The volume occupied by underground plant structures (roots and rhizomes) increases over time (Reed 1993) and porosity gradually decreases. The wetland should be designed conservatively to allow for the diminished porosity.

The SCS recommends a hydraulic residence time of at least 12 days since this residence time has been found empirically to provide adequate removal of BOD_5.

Field Test Method for BOD_5

The field test method uses data from samples collected in the pretreatment unit to calculate hydraulic residence times via the following equation:

$$t = 2.7 (\ln C_i - \ln C_e + \ln F) / 1.1^{(T-20)}, \text{ or} \quad (4.2)$$
$$t = (\ln C_i - \ln C_e + \ln F) / 65K_T$$

where

- t = hydraulic residence time, days
- C_i = constructed wetland influent BOD_5 concentration, mg/L
- C_e = desired constructed wetland effluent BOD_5 concentration, mg/L
- ln = natural logarithm
- F = fraction of BOD_5 that is not removed as settleable solids near the head of the wetland, expressed as a decimal fraction, (soluble BOD_5/total BOD_5)
- T = water temperature, °C
- K_T = temperature-dependent reaction rate constant, days $^{-1}$

The values for C_i and F are determined from samples of the supernatant (the liquid above the solid layer) in the pretreatment unit. A composite sample (several samples combined) should be collected within the unit. Ideally, samples should be collected and analyzed during various seasonal conditions. Because BOD_5 concentrations in these systems can vary widely, and because an adequate safety factor must be assured, the highest sample value should be used to design the system.

The temperature of the water (T) is controlled by local climatic conditions. The lowest water temperature under which the wetland will be expected to perform should be used for the design. In constructed wetlands in the northern states, if the wetland does not freeze completely, the wetland will continue to function and water temperatures under the ice can be estimated as 40°F (5°C)(Boyd 1991). However, at low temperatures, removal rates will be lower and the wetland will have to be larger to accommodate the slower rates. Alternatively, the wastewater can be stored in the pretreatment unit during the cold seasons. In this case, a higher value for water temperature can be used and the wetland made smaller, depending on BOD_5 load, wastewater volume, and local temperatures.

The values to be used for F and K_T in designing constructed wetlands have not been confirmed. The value often used for F in domestic systems is about 0.52. This should be the lower limit for F unless research determines otherwise. If organic material is adequately removed by pretreatment, the value of F can be increased, but it should not be more than 0.90. For an agricultural waste treatment lagoon, the value of F may equal 0.90. A value for K_T of $0.0057 (1.1)^{(T-20)}$ is often used. However, experimental data on the values to be used in designing constructed wetlands have been difficult to obtain because of the logistic and economic difficulties in experimenting with wetlands on a scale large enough to be appropriate. The wetland should be sized generously to accommodate these uncertainties.

The hydraulic characteristics of the constructed wetland should provide the required hydraulic residence time of at least 12 days. The hydraulic design is calculated using the average depth of water and average daily flow rate into the wetland to find an arrangement that results in the required hydraulic residence time:

$$SA = t / (D \times P / Q) \quad (4.3)$$

where

- SA = surface area, ft^2 (length x width)
- t = hydraulic residence time, days
- D = average water depth in the constructed wetland, ft
- P = porosity, percent as a decimal
- Q = average daily flow rate, ft^3/day.

PRESUMPTIVE METHOD FOR NITROGEN

The presumptive method can be modified to design wetlands for nitrogen removal. To treat ammonia to concentrations in the wetland effluent of less than 10 mg/L (the usual discharge limit), Hammer (1992) recommends that influent nitrogen not exceed 9 lb/ac/day as TKN (10 kg/ha/day). To size the constructed wetland for TKN:

1. Determine the production of ammonia:

	Average weight (lb)	Ammonia production (lb) 1000 lb animal unit (AU) per day
Dairy cows	1300	1.6
Beef cattle	750	1.4
Swine	200	2.1
Poultry - layers	4	3.7
Poultry - broilers	2.2	5.1

1. Calculate the concentration of nitrogen (as TKN) per day:

   Assuming that TKN is 150% of ammonia:
   mg/L TKN = mg/L ammonia x 1.5

2. Calculate the daily load of TKN:
   TKN (lb/day) = mg/L TKN x ft^3/hr of influent x 680 (conversion factor)

3. Determine the surface area needed:
   Surface area (SA)(ac) = lb/day TKN ÷ 9 lb TKN ac/day.

CHAPTER 5
SUBSURFACE FLOW WETLANDS

INTRODUCTION

The use of SSF wetlands in agriculture has been limited because of the high probability that they will be clogged by water containing more than about 30 mg/L solids.

The design information provided in this chapter is a summary of the information in *Subsurface Flow Constructed Wetlands for Wastewater Treatment: A Technology Assessment* (Reed 1993). Reed based his recommendations on the performance of 14 municipal, domestic, hospital, and industrial systems that have provided detailed data and that are thought to be representative of constructed wetland systems in the United States. Many of these systems are in the South and West, and most have been operating for less than five years. Only a limited number of systems in the Northeast have provided operational data.

WETLAND DESIGN

Guidelines to designing a SSF constructed wetland are given in table 6. The design assumes that the wastewater has been pretreated to reduce BOD_5 by 70%, TSS to less than 1,500 mg/L, and ammonia to less than 100 mg/L.

Darcy's Law

The intent of the SSF wetland treatment concept is to maintain the flow below the surface of the media in the bed. The design of SSF wetlands has generally been based on Darcy's Law, which describes the flow regime in a porous medium. However, many of the systems designed with Darcy's Law have developed unintended surface flow and may have been under-designed.

Table 6. Design summary for subsurface flow wetlands.

Pretreatment	Reduction of BOD_5 by 70% Reduction of solids to <1,500 mg/L Reduction of ammonia to <100 mg/L
Configuration	Fit the wetland to the site Divide large wetlands into side-by-side cells
Flow	By gravity, as much as possible Subsurface flow design based on Darcy's Law
Bottom slopes	Side-to-side elevations: level Inlet to outlet slopes: almost flat (0.5 - 1.0%)
Inlet	Surface manifold with adjustable outlets
Outlet	Perforated subsurface manifold connected to adjustable outlet
Vegetation	Complete coverage is more important than the species used Use at least two or three different species
Construction	Medium(a) must be clean Wetland must be sealed to limit infiltration and exfiltration Water table must be below or excluded from the wetland

Darcy's Law assumes laminar flow, a constant and uniform flow (Q), and lack of short-circuiting, conditions that do not exist in constructed wetlands (see Volume 1). Darcy's Law is thought to provide a reasonable approximation of the hydraulic conditions in an SSF bed if small to moderate size gravel (<1.5 inches, or <4 cm) is used as the medium, the system is properly constructed to minimize short-circuiting, the system is designed to depend on a minimal hydraulic gradient, and the flow (Q in equation 5.1) is considered to be the "average" flow $[(Q_{in} + Q_{out})/2]$ in the system to account for any gains or losses due to precipitation, evaporation, or seepage.

Darcy's Law is typically defined with equation 5.1:

$$Q = k_s A S \tag{5.1}$$

where

- Q = flow per unit time, (ft^3/day, gal/day, m^3/day, etc.)
- k_s = hydraulic conductivity of a unit area of the medium perpendicular to the flow direction, (ft^3/ft^2/day, gal/day, m^3/m^2/day, etc.)
- A = total cross-sectional area, perpendicular to flow (ft^2, m^2, etc)
- S = hydraulic gradient of the water surface in the flow system (slope of the water table)(dh/dL, ft/ft, m/m).

Systems in the United States and Europe with successful hydraulic performance do so either with a sloping bottom and/or adjustable outlet structures which allow the water level to be lowered at the end of the bed. A sloped bottom or lowering the water level at the end of the bed produces the pressure head required to overcome resistance to flow through the media and thus maintains subsurface flow.

Clogging has occurred in some systems. The clogging is believed to result from the introduction of fine particulate material into the medium because of improper construction procedures. Nevertheless, it is judicious to provide a large safety factor against clogging. A value <1/3 of the "effective" hydraulic conductivity (k_s) is recommended for the design. Also, the design should not use more than 10% of the potential hydraulic gradient in the proposed bed. These two limits, combined with an adjustable outlet for the bed discharge, should ensure a more-than-adequate safety factor in the hydraulic design of the system.

Media Types

Almost all of the SSF constructed wetlands in the United States have used media ranging from medium gravel to coarse rock. The most common substrate is sized (graded), washed gravel. To limit compaction, a gravel with rounded surfaces, such as river rock or bank run gravel, is preferred. After the type and size of the medium have been selected and before the system has been designed, the hydraulic conductivity and porosity of the medium should be determined by field or laboratory testing.

Length-to-Width Ratio

The length-to-width ratio (aspect) of the wetland cell is an important consideration in the hydraulic design of SSF wetland systems since the maximum potential hydraulic gradient is related to the available depth of the bed divided by the length of the flow path. The hydraulic gradient defines the total head available in the system and must be large enough to overcome the resistance to horizontal flow in porous media. Because of these considerations, the length-to-width ratio should be relatively low (in the range of 0.4:1 to 3:1) to provide the flexibility and reserve capacity for future operational adjustments.

The hydraulic conductivity and hydraulic gradient limits used to guard against clogging will also have the practical effect of limiting the length-to-width ratio of the beds to less than 3:1 for 2 ft (0.6 m) deep beds and to about 0.75:1 for 1 ft (0.3 m) deep beds. Using such a low value for hydraulic gradient will help to maintain near-laminar flow in the bed and validate the use of Darcy's Law in the design of the system. Since this approach ensures a relatively wide entry zone, it will also result in low organic loading on the cross-sectional area and thereby lessen concerns over clogging.

Bed Slope

The bottom of the cell can be flat or slightly sloping from top to bottom. The top surface of the medium should be level regardless of the slope of the bottom. A level surface facilitates plant management and minimizes surface flow problems. Once surface flow develops on a downward sloping surface, flow may not penetrate the medium even though the true water level within the medium is well below the surface.

SIZING

Biochemical Oxygen Demand

SSF systems are generally designed for BOD_5 removal. In SSF systems, the physical removal of BOD_5 is believed to occur rapidly through settling and entrapment of particulate matter in the void spaces in the gravel or rock media (Reed 1993).

Most of the existing systems in the United States and Europe have been designed as attached growth biological reactors using the same equations as those used for SF wetlands (equations 4.1 - 4.3). The plug flow model is presently in general use and seems to provide a general approximation of performance. It is believed that the plug flow rate constant for SSF wetlands is higher than for facultative lagoons or SF wetlands because the surface area available on the media in SSF wetlands is much higher than in the other two cases. This surface area supports the attached growth microorganisms that are believed to provide most of the treatment responses in the system. At an apparent organic loading of 98 lb/ac/day (110 kg/ha/day), the rate constant for the SSF wetland (1.104 d^{-1}) is about an order of magnitude higher than that for facultative lagoons, and about double the value often used for SF wetlands.

The "t", or hydraulic residence time factor in equation 4.1 can be defined as:

$$t = nLWd/Q \qquad (5.2)$$

where

n = porosity (% as a decimal)
L = length of bed (ft, m)
W = width of bed (ft, m)
d = average water depth (ft, m)
Q = average flow rate through bed (ft^3/day, m^3/day).

The Q value in equation 5.2 is the average flow in the bed $[(Q_{in} + Q_{out})/2]$, calculated from flow through the bed plus gains and losses from precipitation and evapotranspiration. This is the same value used in Darcy's Law for hydraulic design.

The "d" value in the equation is the average depth of liquid in the bed. If the design hydraulic gradient is limited to 10% of the potential available, as recommended above, then the average depth of water in the bed will be equal to 95% of the total depth of the treatment media in the bed.

Since the term LW in equation 5.1 is equal to the surface area of the bed, rearrangement of terms permits the calculation of the surface area (A_s) required to achieve the necessary level of BOD_5 removal:

$$A_s = L \times W = Q \ln (C_e/C_o) / -k_T dn \qquad (5.3)$$

where

A_s = bed surface area (ft^2)
other terms as defined previously.

The depth of the media selected will depend on the design intentions for the system. If the vegetation is intended as a major source of oxygen for nitrification in the system, then the depth of the bed should not exceed the potential root penetration depth for the plant species chosen. This will ensure the availability of some oxygen throughout the bed profile but may require management practices which assure root penetration to these depths.

The design and sizing of the SSF bed for BOD_5 removal is an iterative process:

1. Determine the media type, vegetation, and depth of bed to be used.
2. By field or laboratory testing, determine the porosity (n) and "effective" hydraulic conductivity (k_s) of the media to be used.
3. Use equation 5.3 to determine the required surface area of the bed for the desired levels of BOD_5 removal.
4. Depending on site topography, select a preliminary length-to-width ratio; 0.4:1 up to 3:1 are generally acceptable.
5. Determine bed length (L) and width (W) for the previously assumed length-to-width ratio, and the results of step 2.
6. Using Darcy's Law (equation 5.1) with the previously recommended limits (ks ≤1/3 of the "effective" value, hydraulic gradient ≤10% of maximum potential), determine the flow (Q) that can pass through the bed in subsurface flow. If the resulting Q is less than the actual design flow, then surface flow is possible. In this case, the L and W values must be adjusted until the Darcy's Q is equal to or greater than the design flow.
7. It is not valid to use equation 5.3 with effluent BOD_5 (C_e) values below 5 mg/L, since wetlands export a BOD_5 residual due to decomposition of the natural organic detritus in the system.

SSF wetlands, along with other systems such as facultative lagoons and land treatment systems, have displayed a near linear relationship between mass organic loading and mass removal rates. However, caution is necessary when discussing mass organic loadings, since the data are not actual areal loadings, but rather the "apparent" organic loadings obtained by dividing the daily organic load by the total surface area. This implies that the organic load is applied uniformly over the entire surface of the wetland. Much of the input solids and BOD_5 are probably removed rapidly near the front of the system, so the actual organic loading on this zone is much higher than on the rest of the system (unless step-feeding, recirculation, or both is used in the design). The non-uniform application of organic wastes complicates the development of an accurate and precise design model for BOD_5 removal since it is likely that the actual removal rates may vary along the flow path while, concurrently, residual BOD_5 is being produced from decomposing plant detritus. The development of the ultimate design model must wait for the collection of a sufficient body of reliable data describing the internal performance within these systems.

Total Suspended Solids

A kinetic design model is not available for TSS, but TSS removal apparently follows the same pattern as BOD_5. It is assumed that a system designed for a certain level of BOD_5 removal will remove a comparable level of TSS as long as significant, long-term surface flow does not occur.

Nitrogen

The major pathway for nitrogen removal in SSF wetlands is biological nitrification followed by denitrification. The controlling factor in ammonia removal is the availability of oxygen in the substrate. In continually saturated beds, leakage of oxygen from the roots of plants is the major source of oxygen.

Two systems demonstrating excellent ammonia removal have plant roots (and therefore some available oxygen) throughout the profile, and sufficient residence time to complete the reaction. Data from these systems suggest a two-stage system in which the BOD_5 is decreased to about 20 mg/L, followed by nitrification with oxygen supplied by the vegetation. The limiting factor in this case is the rate at which the plants can provide oxygen. The extent to which plants can provide oxygen is unknown at this time. The remaining BOD_5 in the second stage would then be available for denitrification.

Alternative methods for nitrification include shallow overland flow, mechanical aeration after BOD_5 removal, providing open water zones for surface reaeration, and using parallel cells operated on a batch-type fill and draw basis to allow atmospheric oxygen to be introduced into the substrate.

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ABBREVIATIONS AND CONVERSION FACTORS

MULTIPLY	BY	TO OBTAIN
ac, acre	0.4047	ha, hectare
cfs, cubic foot per second	448.831	gpm, gallon per minute
cfs, cubic foot per second	2.8317×10^{-2}	m^3/s, cubic meter per second
cm, centimeter	0.3937	inch
cm/sec, centimeter per second	3.28×10^{-2}	fps, foot per second
°F, degree Fahrenheit	5/9 (°F - 32)	°C, degree Celsius
ft, foot	0.305	m, meter
ft^2, square foot	9.29×10^{-2}	m^2, square meter
ft^3, cubic foot	2.83×10^{-2}	m^3, cubic meter
ft/mi, foot per mile	0.1895	m/km, meter per kilometer
fps, foot per second	18.29	m/min, meter per minute
g/m^2/day, gram per square meter per day	8.92	lb/ac/day, pound per acre per day
gal, gallon	3.785	L, liter
gal, gallon	3.785×10^{-3}	m^3, cubic meter
gpm, gallon per minute	6.308×10^{-2}	L/s, liter per second
ha, hectare	2.47	ac, acre
inch	2.54	cm, centimeter
kg, kilogram	2.205	lb, pound
kg/ha/day, kilogram per hectare per day	0.892	lb/ac/day, pound per acre per day
kg/m^2, kilogram per square meter	0.2	lb/ft^2, pound per square foot
L, liter	3.531×10^{-2}	ft^3, cubic foot
L, liter	0.2642	gal, gallon
lb, pound	0.4536	kg, kilogram
lb/ac, pound per acre	1.121	kg/ha, kilogram per hectare
m, meter	3.28	ft, foot
m^2, square meter	10.76	ft^2, square foot
m^3, cubic meter	1.31	yd^3, cubic yard
m^3, cubic meter	264.2	gallon, gal
m^3/ha/day, cubic meter per hectare per day	106.9	gallon per day per acre, gpd/ac
mm, millimeter	3.94×10^{-2}	inch
mi, mile	1.609	kilometer, km

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