843F00001

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 2

DOMESTIC WASTEWATER

ACKNOWLEDGMENTS

Many people contributed to this Handbook. An Interagency Core Group provided the initial impetus for the Handbook, and later provided guidance and technical input during its preparation. The Core Group comprised:

Carl DuPoldt, USDA - NRCS, Chester, PA
Robert Edwards, Susquehanna River Basin Commission, Harrisburg, PA
Lamonte Garber, Chesapeake Bay Foundation, Harrisburg, PA
Barry Isaacs, USDA - NRCS, Harrisburg, PA
Jeffrey Lapp, EPA, Philadelphia, PA
Timothy Murphy, USDA - NRCS, Harrisburg, PA
Glenn Rider, Pennsylvania Department of Environmental Resources, Harrisburg, PA
Melanie Sayers, Pennsylvania Department of Agriculture, Harrisburg, PA
Fred Suffian, USDA - NRCS, Philadelphia, PA
Charles Takita, Susquehanna River Basin Commission, Harrisburg, PA
Harold Webster, Penn State University, DuBois, PA.

Many experts on constructed wetlands contributed by providing information and by reviewing and commenting on the Handbook. These individuals included:

Robert Bastian, EPA ,Washington, DC
William Boyd, USDA - NRCS, Lincoln, NE
Robert Brooks, Penn State University, University Park, PA
Donald Brown, EPA, Cincinnati, OH
Dana Chapman, USDA - NRCS, Auburn, NY
Tracy Davenport, USDA - NRCS, Annapolis, MD
Paul DuBowy, Texas A & M University, College Station, TX
Michelle Girts, CH2M HILL, Portland, OR
Robert Hedin, Hedin Environmental, Sewickley, PA
William Hellier, Pennsylvania Department of Environmental Resources, Hawk Run, PA
Robert Kadlec, Wetland Management Services, Chelsea, MI
Douglas Kepler, Damariscotta, Clarion, PA
Robert Kleinmann, US Bureau of Mines, Pittsburgh, PA
Robert Knight, CH2M HILL, Gainesville, FL
Fran Koch, Pennsylvania Department of Environmental Resources, Harrisburg, PA
Eric McCleary, Damariscotta, Clarion, PA
Gerald Moshiri, Center for Wetlands and Eco-Technology Application, Gulf Breeze, FL
John Murtha, Pennsylvania Department of Environmental Resources, Harrisburg, PA
Robert Myers, USDA - NRCS, Syracuse, NY
Kurt Neumiller, EPA, Annapolis, MD
Richard Reaves, Purdue University, West Lafayette, IN
William Sanville, EPA, Cincinnati, OH
Dennis Sievers, University of Missouri, Columbia, MO
Earl Shaver, Delaware Department of Natural Resources and Environmental Control, Dover, DE
Daniel Seibert, USDA - NRCS, Somerset, PA
Jeffrey Skousen, West Virginia University, Morgantown, WV
Peter Slack, Pennsylvania Department of Environmental Resources, Harrisburg, PA
Dennis Verdi, USDA - NRCS, Amherst, MA
Thomas Walski, Wilkes University, Wilkes-Barre, PA
Robert Wengryznek, USDA - NRCS, Orono, ME
Alfred Whitehouse, Office of Surface Mining, Pittsburgh, PA
Christopher Zabawa, EPA, Washington, DC.

This document was prepared by Luise Davis for the USDA–Natural Resources Conservation Service and the US Environmental Protection Agency–Region III, in cooperation with the Pennsylvania Department of Environmental Resources. Partial funding has been provided with nonpoint source management program funds under Section 319 of the Federal Clean Water Act.

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.

PS5384RSEZ

VOLUME 2
CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

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

Constructed wetlands can provide an inexpensive and easily managed means of removing 5-day biochemical oxygen demand, particulates, nutrients, and bacteria from domestic wastewater. Constructed wetlands for domestic wastewater have found a wide range of applications, ranging from large municipal systems to single family homes. Constructed wetlands can provide year-round treatment but are readily adaptable to seasonal or occasional uses, for instance, at parks, camps, and schools. Some systems have focused on maximizing the amount of wastewater treated on the smallest amount of land possible while other systems have focused on polishing pretreated effluents with larger wetlands that provide wildlife habitat and aesthetics in addition to water quality improvement. Constructed wetlands can be used to upgrade the performance of existing facilities or as a component of new wastewater treatment systems.

A number of documents have been published recently on the use of constructed wetlands in treating domestic wastewater. These publications include:

Center for Environmental Resource Management. 1993. *Proceedings Subsurface Flow Constructed Wetlands Conference.* University of Texas-El Paso, El Paso, TX.

EC/EWPCA. 1990. *European Design and Operations Guidelines for Reed Bed Treatment Systems.* P. F. Cooper (ed.), Proceedings International Conference on the Use of Constructed Wetlands in Water Pollution Control. Pergamon Press, Oxford, UK.

Reed, S. C. 1993. *Design of Subsurface Flow Constructed Wetlands For Wastewater Treatment: a Technology Assessment.* EPA 832-R-93-001. EPA Office of Wastewater Management, Washington, DC.

Environmental Protection Agency. 1988. *Design Manual: Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment.* EPA/625/1-88/022. Center for Environmental Research, Cincinnati, OH.

Reed, S. C., E. J. Middlebrooks, and R. W. Crites. 1994. *Natural Systems for Waste Management and Treatment.* 2nd edition. McGraw-Hill Book Company, New York City, NY.

Water Pollution Control Federation. 1990. *Natural Systems for Wastewater Treatment,* Manual of Practice FD-16, Chapter 9. Alexandria, VA.

Water Science and Technology, Volume 29. 1994.

The National Small Flows Clearinghouse (NSFC) at West Virginia University, Morgantown, West Virginia (telephone 1-800-624-8301) provides technical assistance and information to small communities.

The Environmental Protection Agency (EPA) has sponsored a project to collect and catalog information from wastewater treatment wetlands into a computer database. The Wetlands Treatment Database (North American Wetlands for Water Quality Treatment Database)(Knight, R. L., R. W. Ruble, R. H. Kadlec, and S. C. Reed 1994) is available on 3.5" diskette. To order, contact: Don Brown, USEPA (MS-347), Cincinnati, OH 45268; phone: (513) 569-7630; fax: (513) 569-7677; e-mail: brown.donald@epamail.epa.gov.

While much experience has been gained in the design of constructed wetland systems for domestic wastewater, much is not yet understood and many of the relationships between design and performance have not been clearly established. Constructed wetland technology continues to be refined as more systems are installed and monitored 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.

CHAPTER 2
USING CONSTRUCTED WETLANDS TO TREAT DOMESTIC WASTEWATER

INTRODUCTION

Domestic wastewaters contain large amounts of nutrients, particulates, and organic matter that must be removed before the water can be discharged. Constructed wetlands are highly effective in removing 5-day biochemical oxygen demand (BOD_5) and total suspended solids (TSS) from pretreated domestic wastewater. Removal efficiencies for nitrogen, particularly ammonia, vary considerably, depending on system design, retention time, and the oxygen available for nitrification. Phosphorus removal may be limited in the long-term, although good removal may be seen during the first several years. The numbers of pathogenic bacteria and viruses are significantly decreased during passage through constructed wetlands. Removal capabilities are discussed in Chapter 3.

CONTAMINANT REMOVAL PROCESSES

Wetlands remove contaminants through a series of interacting physical, chemical, and biological processes, including filtration, sedimentation, adsorption, precipitation and dissolution, volatilization, and biochemical interactions (table 1).

The suspended solids that remain after pretreatment are removed in the wetland mainly by sedimentation and filtration. These physical processes also remove a significant portion of other wastewater constituents, such as BOD_5, nutrients, and pathogens, that are associated with the solids.

Adsorption is the principal removal mechanism for dissolved pollutants such as phosphorus and dissolved metals. Adsorption is promoted by the large amount of surface area provided by the sediments, vegetation, soils, and litter.

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

Wastewater Constituent	Removal Mechanisms
Biochemical oxygen demand	Microbial degradation (aerobic and anaerobic) Sedimentation (accumulations 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 Attack by antibiotics excreted from the roots of wetland plants Predation by invertebrates and other microbes

Soluble organic compounds are, for the most part, degraded by microbes, especially bacteria, that grow on the surfaces of the plants, litter, and the substrate. The oxygen needed to support aerobic microbial processes is supplied by diffusion from the atmosphere, by photosynthetic oxygen production within the water column, and, to some extent, by leakage of oxygen from the roots of the vegetation. Some anaerobic microbial degradation also occurs.

ADVANTAGES AND LIMITATIONS OF CONSTRUCTED WETLANDS

When properly designed, constructed wetlands offer a number of advantages, including low cost, simplicity of operation, and effective removal of BOD_5 and TSS (table 2). When sized adequately, constructed wetlands are also tolerant of fluctuating flows and variable water quality. For instance, at the Des Plaines River Wetlands Demonstration Project, effluent concentrations of TSS, nitrate, and total phosphorus remained low and steady although influent concentrations were often quite high and varied significantly with time (Hey et al. 1994).

Constructed wetland treatment is constrained by a number of limitations, including relatively large land requirements and a degree of uncertainty not found in more conventional approaches (table 2).

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 to operate as possible while ensuring reliable treatment. Building a slightly larger system may be more expensive to construct but may be more reliable and less costly to operate than a smaller system. Attention to several factors will help to ensure successful wetland treatment:

- Adequate pretreatment. Pollutant loads in raw wastewater can exceed the ability of a wetland to treat or assimilate them. Wetland treatment is suitable for waters that have received primary or secondary treatment.
- Adequate retention time. A wetland treats wastewater through a number of biological (largely microbial), physical, and chemical processes. The water must remain in the

Table 2. Advantages and limitations of constructed wetland treatment of domestic wastewater.

Advantages	Limitations
Excellent removal of BOD_5 and TSS	Variable treatment efficiencies due to the effects of season and weather
Good removal of nutrients, depending on system design	Uncertainty as to treatment effectiveness under all conditions
Ability to handle daily or seasonally variable loads	Sensitivity to high ammonia levels
Low energy and maintenance requirements	Larger land area requirement than for conventional treatment
Simplicity of operation	Potential for mosquito production

wetland long enough for biological and chemical transformations to take place and for 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. Wetland plants are generally tolerant of fluctuating flows, but they cannot withstand complete drying. For this reason, either a fairly regular supply of wastewater must be assured or a supplemental source of water must be provided.
- 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 wastewater input streams accordingly. While wetlands are low maintenance systems, they are not maintenance-free. For instance, distribution systems must be cleaned periodically to avoid plugging and uneven distribution of flow, and valves and piping must be checked to detect and correct blockages or leaks.

TYPES OF CONSTRUCTED WETLANDS

Domestic wastewater can be treated with surface flow (SF) or subsurface flow (SSF) 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 handle wide variations in flow. SF systems can provide excellent removal of BOD_5 and TSS and some installations have achieved good removal of ammonia and total nitrogen. SF systems are similar to natural marshes and can provide wildlife habitat as well as wastewater treatment. SF wetlands are discussed in Chapter 4.

In SSF wetlands, the water level is intended to remain below the surface of the substrate. Since the water is not exposed to the atmosphere, potential problems with insects, odors, and safety are

Table 3. Guidelines for creating constructed wetlands.

Know what you are dealing with:	Sample the wastewater Know what pretreatment will accomplish
Wetlands must have water:	Know the water budget
Size the wetland generously:	An undersized wetland cannot perform well
Give the plants a chance:	Allow time for establishment Avoid shock loadings
Don't overload the wetland:	Application rates must not exceed treatment rates
Protect the wetland from toxics:	Limit the toxics entering the wetland Keep herbicides out of the wetland
Keep an eye on what is happening:	Monitoring is needed to assure continued performance
Get interdisciplinary help:	Environmental engineer Water quality specialist Plant materials specialist or biologist State agencies

avoided. There is debate over the most effective length-to-width ratio, type of vegetation, and type and size of medium. A few recent European designs have incorporated vertical flow and batch loading in an attempt to promote more effective wetting and drying cycles, and to entrain more oxygen for nitrification (Bastian and Hammer 1993). Because of the hydraulic constraints imposed by the media, SSF wetlands are best suited to the treatment of wastewaters under relatively uniform flow conditions. There have been problems with surface flow and apparent plugging. SSF wetlands are discussed in Chapter 5.

WASTEWATER CHARACTERISTICS

To design the wetland treatment system, an accurate assessment of contaminant loadings is needed (loading = contaminant concentration x water volume). To calculate loadings, data are needed on the average water quality; the maximum concentrations, and the largest and smallest volumes that may occur. Maximum concentrations will probably occur in late summer when 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 contaminant loadings.

Water Quality

For design, water quality analyses generally include:

- pH
- alkalinity
- 5-day biochemical oxygen demand (BOD_5)
- total suspended solids (TSS)
- total dissolved solids (TDS)
- dissolved oxygen
- nitrate plus nitrite nitrogen ($NO_2 + NO_3$-N)
- ammonia nitrogen (NH_3-N)
- total phosphorus
- heavy metals (for instance, lead, mercury, chromium, zinc)
- refractory organics
- total or fecal coliform bacteria.

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.

Water Quantity

An accurate estimate of the volume of wastewater is needed, including the expected average, maximum, and minimum flows. The level of detail required (daily, monthly, or seasonal flows) will be project-specific. The frequency and duration of freezing conditions must be estimated to determine if storage or special operating practices will be needed to address wintertime conditions.

If extended periods of low or no flow are expected, as, for instance, at camps, parks, or schools, the extreme low flows must be determined to calculate the volume of supplemental water that will be required to maintain flow through the wetland during low flow periods.

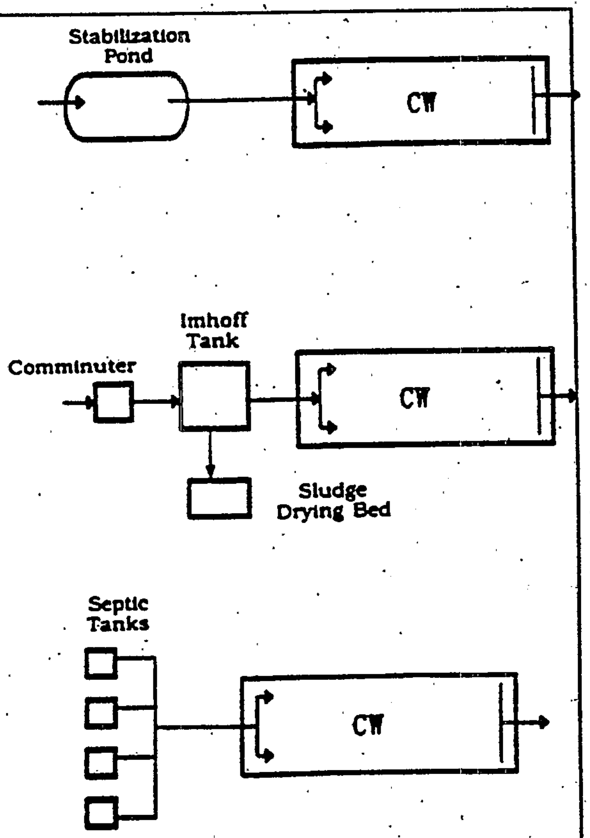
PRETREATMENT

The equivalent of primary treatment is considered the minimum acceptable level of pretreatment for municipal wastewaters. Septic tanks, recirculating sand filters, Imhoff tanks, ponds, and disk screens, as well as conventional primary treatment, have been used for pretreatment. Pretreatment to lower total organic loading can help to control mosquitoes and odors.

If toxics are a significant component of the wastewater to be treated, adequate pretreatment to reduce toxics must be provided to protect the microbial community and other biological components of the wetland.

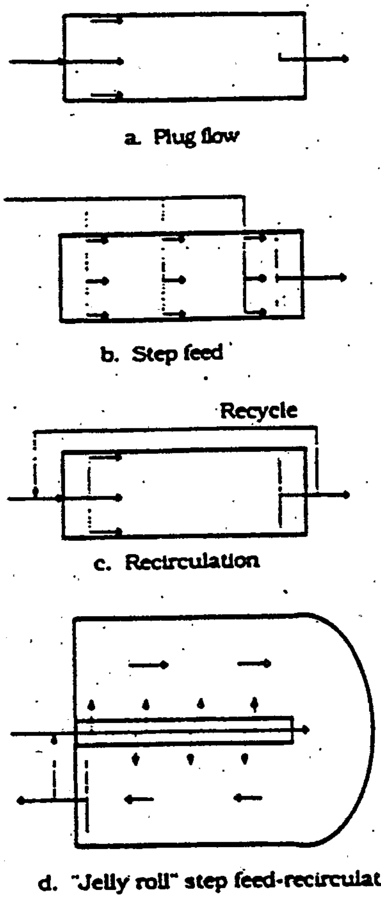
SYSTEM CONFIGURATION

Various configurations are possible for the constructed wetland and for incorporating it into a treatment system (figures 1 and 2). System configuration includes length-to-width ratio (sometimes called "aspect"), compartmentalization, and the location of single or multiple discharge points. The configuration should take advantage of the natural topography of the site to minimize excavation and grading costs. While wetlands are often designed as rectangles, wetlands can be built in almost any shape to fit the topography of the site.



CW: Constructed Wetland

Figure 1. Configuration options for constructed wetlands (from Steiner and Freeman 1989).



CW: Constructed Wetland

Figure 2. Flow patterns for constructed wetlands (from Steiner and Freeman 1989).

Whatever the configuration, care must be taken to ensure equal flow distribution at the inlet and to avoid short-circuiting of flow to the outlet.

LENGTH-TO-WIDTH RATIO

Many SF constructed wetland have been designed with an overall length-to-width ratio of about 3:1 to 4:1. This ratio has been thought to lower excessive loading at the inlet of early systems built with high length-to-width ratios and to provide good removal of BOD_5 and TSS. The concern was that in a longer, narrower wetland the upper end might become overloaded while the lower end might lack adequate nutrients. However, the relationships between length-to-width ratios and performance has not been adequately studied and an optimal length-to-width ratio has not been determined.

For SSF wetlands, the length-to-width ratio of the wetland cell is an important consideration in the hydraulic design since the maximum potential hydraulic gradient is related to the available depth of the bed divided by the length of the flow path. Cell length can be limited by hydraulic capacity if surface flow is to be avoided. Therefore, SSF wetlands may have length-to-width ratios larger or smaller than 1:1. It is thought that most of the removal takes place in the vicinity of the influent area and that systems with relatively high BOD_5 discharge requirements can therefore achieve adequate BOD_5 and TSS reductions with relatively short length-to-width ratios (Reed 1993). In many of the early SSF systems that were designed with a ratio of 10:1 or more and a total depth of 2 ft (0.6 m), surface flow has developed. The surface flow is thought to result from inadequate hydraulic gradients (Reed 1993).

COMPARTMENTALIZATION

Compartmentalizing the wetland with several cells arranged in series or in parallel is suggested because it allows flows to be redistributed through the system as necessary for maintenance or repair. Cells arranged in parallel facilitate the maintenance of plant communities (because of the greater edge length relative to surface area) and allow different plant populations and any associated plant diseases or pathogens to be isolated. Ideally, cells can be arranged to permit operation in series or in parallel, with alternate discharge points and interconnections.

STEP-FEEDING

Step-feeding, which is the use of multiple input points along the length of a cell, has been suggested as a means of distributing organic loads along the length of the wetland, thereby lessening the organic loading on the upper end of the cell. The additional capital and operating costs of step-feeding need to be weighed against the potential benefits gained.

RECYCLING

It may be advantageous to recycle all or a portion of the wetland effluent. Recycling can be used to dilute influent BOD_5 and solids. Recycling may increase dissolved oxygen concentrations and detention time, which in turn may enhance nitrification and nitrogen removal. Recycling is also an efficient way to maintain adequate flow during low-flow periods.

The disadvantages of recycling are the increased construction costs and increased operation (pumping) costs. A wrap-around design may help to minimize these costs. Also, recycling may slowly increase salinities as evapotranspiration removes water from the system. The added costs of recycling must be weighed against the potential benefits gained.

CHAPTER 3
PERFORMANCE EXPECTATIONS

INTRODUCTION

Perhaps more is known about the domestic wastewater applications of constructed wetlands than for any other use. A database on wastewater treatment wetlands has been compiled by EPA's Risk Reduction Engineering Laboratory (Knight et al. 1994). The database contains data from 323 wetland cells at 178 locations in the United States and Canada, and includes information on natural and constructed wetlands, and SF, SSF, and hybrid systems. The majority of the systems in the database have been installed recently and have as yet produced little operational data. Performance data for 11 SF and 2 SSF domestic wastewater constructed wetlands that have been operating long enough to produce useful data are summarized in table 4.

BIOCHEMICAL OXYGEN DEMAND AND TOTAL SUSPENDED SOLIDS

BOD_5 is removed by filtration and sedimentation of particulate matter and by microbial degradation of soluble BOD_5. The organic matter in treatment wetlands provides a source of energy for populations of bacteria, fungi, and aquatic macroinvertebrates similar to those in conventional activated sludge and trickling filter treatment plants. In SSF wetlands, physical removal of BOD_5 is believed to occur rapidly through settling and entrapment of particulate matter in the void spaces in the media.

Both SF and SSF wetlands are extremely efficient at assimilating BOD_5 and TSS (table 4).

Table 4. Summary of municipal constructed wetland operational data (adapted from Knight et al. 1993).

	BOD_5 (mg/L)			TSS (mg/L)			NH_3-N (mg/L)			TP (mg/L)		
	In	Out	%	In	Out	%	In	Out	%	In	Out	%
Surface Flow Wetlands												
Benton-cattail	26	10	62	57	11	82	7.7	7.9	inc	4.5	4.2	7
Benton-woolgrass	26	12	52	57	16	73	7.7	6.4	16	4.5	4.0	12
Cobalt	21	5	78	36	28	23	2.9	1.0	65	1.7	0.8	54
Gustine 1A	130	50	62	73	40	46	17.0	16.1	6	-	-	-
Gustine 1B	130	27	79	81	23	72	16.3	17.9	inc	-	-	-
Gustine 1C	145	24	83	88	57	36	18.4	20.4	inc	-	-	-
Gustine 1D	141	30	78	98	20	79	19.6	22.9	inc	-	-	-
Gustine 2A	151	45	70	100	34	66	18	23.2	inc	-	-	-
Kelly Farm	-	-	-	-	-	-	8.4	0.1	99	-	-	-
Moodna Basin	53	18	66	34	12	64	20.4	11.4	44	-	-	-
Norwalk	229	9	96	232	33	86	-	-	-	-	-	-
Subsurface Flow Wetlands												
Kingston	56	9	84	83	3	96	22	16	27	3.4	2.1	38
Monterey	38	15	60	32	7	78	9.3	8.7	7	-	-	-

%: percent reduction
inc: increase

Constructed wetland treatment systems commonly receive inflow BOD_5 concentrations of 10 to 100 mg/L, depending on the degree of pretreatment (Knight et al. 1993). For the constructed wetland systems summarized in table 4, removal efficiencies for BOD_5 were generally greater than 60% for both SF and SSF wetlands. These efficiencies were realized in spite of widely varying retention times, configurations, input concentrations, and wetland plant communities (Water Pollution Control Federation 1990).

Knight et al. (1993) found that typical BOD_5 mass removal efficiencies were near 70% or more at mass loading rates up to 250 lb/ac/day (280 kg/ha/day) for SF and SSF wetlands. Lower removal efficiencies occurred, especially when mass loadings were less than 45 lb/ac/day (50 kg/ha/day). A linear regression of 324 municipal, stormwater, and other data records used to examine the predictability of BOD_5 outflow concentration as a function of BOD_5 inflow concentration and hydraulic loading (figure 3) produced the following relationship:

$$\mathrm{BODOUT} = 0.097 \cdot \mathrm{HLR} + 0.192 \cdot \mathrm{BODIN} \qquad R^2 = 0.72$$

where

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

While average annual removal rates were generally high, rates sometimes varied considerably on a monthly or seasonal basis. 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, as well as promoting filtration and sedimentation.

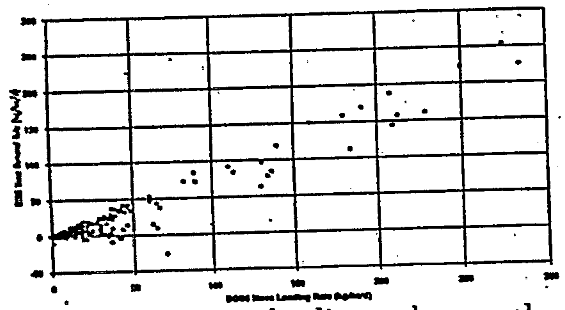


Figure 3. BOD_5 mass loading and removal rates in wetland treatment systems (from Knight et al. 1993).

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 from 2 to 7 mg/L is often present in the wetland effluent (Reed 1993). This internal production of BOD decreases efficiencies at very low inflow concentrations.

The potential for wetlands to assimilate TSS is similar to the potential for BOD_5 removal (table 4). Removal rate and efficiency are consistently high up to loading rates of 135 lb/ac/day (150 kg/h/day) (Knight et al. 1993). Removal efficiencies for TSS are also closely related to input concentration, with lower efficiencies measured at low input concentrations. Cooper et al. (1993) found that TSS removals increased with increasing accumulation of plant detritus in the litter layer.

NITROGEN

The organic nitrogen entering a treatment wetland is usually associated with particulate material, such as algae (especially when pretreatment ponds are used) and organic wastewater solids. Plant detritus generated within the wetland can also be source of organic nitrogen.

In wetlands, nitrogen occurs in a number of forms, the most important of which are nitrogen gas (N_2), nitrite (NO_2), nitrate (NO_3), ammonia (NH_3), and ammonium (NH_4^+). The forms of nitrogen most often regulated are ammonia and total nitrogen (TN). Un-ionized ammonia can be toxic to fish and other aquatic life while excess nitrogen contributes to the over-enrichment of natural waters.

In contrast to the simplicity of BOD and TSS removal, the chemistry of nitrogen removal is complex (figure 4). The removal processes include some that require oxygen (aerobic reactions) and others that take place in the absence of oxygen (anaerobic reactions). Decomposition and mineralization processes in the wetland convert a significant part of organic nitrogen to ammonia. Ammonia is then 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

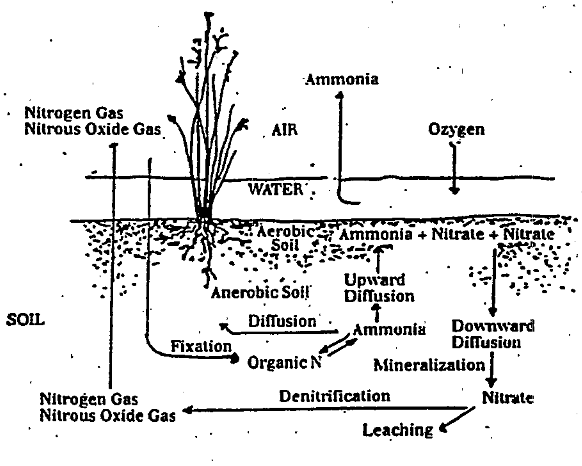


Figure 4. Nitrogen transformations (after Gambrel and Patrick 1978, cited in Mitsch and Gosselink 1986).

Since nitrification is an aerobic process, rates are controlled by the availability of oxygen to the nitrifying bacteria. The process of nitrification is usually limited by the availability of dissolved oxygen availability, and also by temperature and retention time (Knight et al. 1993). Denitrification is usually very rapid and the loss of nitrogen gas to the atmosphere represents a limitless sink. Decaying plant litter may provide anoxic sites for denitrification (Crumpton et al. 1993)

Some nitrogen is taken up by plants and incorporated into plant tissue, but this removal pathway is of limited importance in wetlands in the northeastern United States because the above-ground parts of most emergent plants die back yearly and because below-ground tissue increases only very slowly (Brix 1993). Most of the nitrogen bound in plant tissue is returned to the wetland when the plants die and decay.

Many constructed wetlands, both SF and SSF, are unable to meet typical NPDES limits for ammonia. Reed and Brown (1992) believe that the factor responsible in both cases is the insufficient availability of oxygen to support the activity of the nitrifying organisms. In the SF case, the water may be too deep and the vegetation too dense for wind and turbulence of the water surface to allow for significant aeration. One attempt to correct this problem combines overland flow with a SF wetland. The water depth in the overland flow segment is less than 2 inches (5 cm) deep, which allows for effective aeration and nitrification. Hammer (1992) suggests a marsh-pond-marsh sequence to increase the available oxygen: the water passes through an SF wetland area to convert organic nitrogen to ammonia, then through a pond (a deeper, open water area) for nitrification of ammonia to nitrate and subsequent denitrification to nitrogen gas, then through another wetland area to complete the denitrification of nitrate. In SSF systems, the roots of the vegetation may not penetrate deeply enough and an anaerobic layer develops at the bottom of the wetland. For this reason, SF wetlands may have higher nitrogen removal capacities than SSF wetlands.

Of 12 SSF systems in the southern United States, most showed a marginal or negative ammonia removal rate (in half of the systems output ammonia levels were near or higher than input levels) regardless of detention time in the system (Reed 1993). However, two systems showed very high removal rates at hydraulic retention times (HRT) comparable to the other systems. The difference is believed to be lack of algae, availability of oxygen, and sufficient HRT in the two systems, so that high levels of nitrification can occur. In both cases, the roots penetrated to the bottom of the bed. In the 12 systems with poor nitrogen removal, roots did not penetrate the entire depth of the bed; flow therefore passed through the beds below the root zones where oxygen was not likely to be present.

The depth of the media in most systems in the United States is about 2 ft (0.6 m) but in most cases the plant roots only penetrate to about 1 ft (0.3 m). Deeper penetrations were observed when nutrient levels in the water were low or when plants were located at the sides of the cells where there was less flow than in the main portion of the bed. The use of parallel cells operated on a batch-type fill and draw basis to allow atmospheric oxygen to be introduced into the substrate has also been used to increase ammonia removal.

TN removal has been highly correlated to loading rates as high as 10 kg/ha/day, with removal efficiencies typically between 75 and 95% (Water Pollution Control Federation 1990). With loading rates between 10 and 80 kg/ha/day, total nitrogen removal efficiency varies widely, with some systems showing high values and others much lower values. TN removal efficiency is highly dependent on HRT and decreases significantly at design HRTs of less than about 5 days (Water Pollution Control Federation1990). Phipps and Crumpton (1994) found that seasonal variations in nitrate and organic nitrogen loads had significant effects on the effectiveness of constructed wetlands as sinks for TN: during periods of high nitrate loading, the wetlands were nitrogen sinks while the wetlands were nitrogen sources during periods of low nitrate loading.

Knight et al. (1993) found that, unlike BOD_5, removal efficiencies for TN declined at mass loading rates above 20 kg/ha/day. Also, mass removal efficiencies were more consistent at lower mass loading rates than they were for BOD_5. A regression predicting TN outflow concentration based on hydraulic loading rate (HLR) and TN inflow concentrations was developed from 213 records in the EPA database (figure 5). The multiple linear regression can be expressed as:

$$\mathrm{TNOUT} = 0.28 * \mathrm{HLR} + 0.33 * \mathrm{TNIN}$$
$$R^2 = 0.54$$

where

TNOUT = TN outflow concentration, mg/L
TNIN = TN inflow concentration, mg/L
HLR = Hydraulic loading rate, cm/day.

Based on this equation, TN removal is more dependent on the effect of high HLRs than is BOD_5 removal (Knight et al. 1993).

TN can be generated in wetlands through nitrogen fixation, in which certain plants convert atmospheric nitrogen into the organic form. Many wetland plants are able to fix nitrogen and natural background concentrations of TN are generally in the range of 0.5 to 3 mg/L. Apparently because of this natural nitrogen fixation process, TN removal efficiency decreases when TN input concentrations approach background (Water Pollution Control Federation 1990).

PHOSPHORUS

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

The long-term removal of phosphorus by wetlands is limited. The major sink for phosphorus in most wetlands is the soil. Phosphorus may be buried in organic form in peats or chemically adsorbed in complexed forms with aluminum, iron, or calcium (Faulkner and Richardson 1989). Soil adsorption can result in 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.

Removal at the SF and SSF wetland systems listed in table 4 ranged from 7% to 95%. The extra removal seen in some wetlands may be explained by the export of organisms with their associated phosphorus loads or by chemical adsorption and precipitation of phosphorus and its subsequent burial in the sediments.

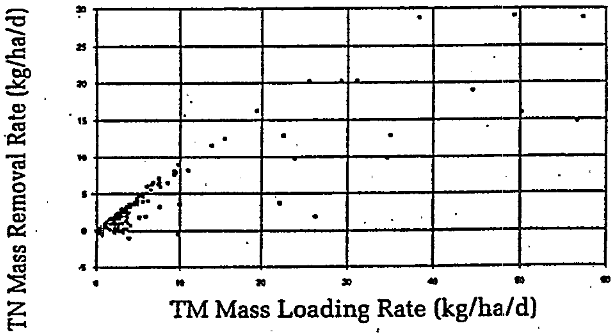


Figure 5. Total nitrogen mass loading and removal rates in wetland treatment systems (from Knight et al. 1993).

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 is an option. In this case, the substrate and accumulated litter must be removed, a new substrate provided, and the wetland replanted. A substrate with high phosphorus-binding capacity should be used.

TOXICS

Toxic compounds are of concern because of their potential effects on the biota of the wetland and on the receiving waters. Metals and other toxics are captured in constructed wetlands through a number of mechanisms, including cation exchange with soils, oxidation in the water column followed by precipitation, and complexing with organic material in the sediments. For volatile chemicals, loss to the atmosphere may be the dominant removal pathway.

The ability of a wetland to assimilate nonvolatile chemicals and chemicals that do not degrade to nontoxic forms is limited and the available storage capacity of a wetland can be exceeded unless adequate pretreatment is provided. While wetlands are able to capture limited amounts of metals and other persistent toxics, wetlands cannot be relied upon to retain unlimited amounts. Periodic effluent monitoring is required to assess whether metals are being retained.

PATHOGENS

Pathogens are of concern because of possible human contact and also because of possible contamination of fish and shellfish harvested for human consumption. Pathogens are removed by die-off, filtration, predation, and adsorption on solids. In general, pathogenic microorganisms are highly host-specific and do not survive long apart from the host.

Constructed wetlands can provide high percentage removals of pathogens and have been shown to be capable of removing bacterial and viral indicators at efficiencies of 90% to 99% at HRTs of three to six days (Ives 1988). At HRTs of three to six days, constructed wetlands are thought to be at least equivalent and, in most cases, more effective than conventional wastewater treatment systems in removing disease-causing bacteria and viruses.

Constructed wetlands treatment typically decreases total coliform levels to 10^3 total coliform/100 ml or less when undisinfected secondary wastewaters from conventional treatment systems are being treated. SF wetland systems are generally capable of a one- to two-log reduction in fecal coliforms (EPA 1993), which in many cases is not enough to routinely satisfy discharge requirements. Peak flows resulting from intense rainfall also disrupt removal efficiencies for fecal coliforms. As a result, many systems use some form of final disinfection.

Removal of bacteria and viruses by wetlands is increased by densely vegetated cells and by longer retention times. Storage in wetlands, as in ponds, can be an effective means of reducing bacteria and viruses.

Where virus removal is of concern, the design can be adjusted to optimize viral removal. Since suspended solids (algal cells and colloidal clay particles) play a key role in removing viruses from the water column, the design should incorporate means to supply the necessary adsorption sites, for instance, by encouraging the accumulation of fine sediments and the growth of unicellular algae. The production of adsorption sites and removal of virus-laden particles should occur sequentially through a series of densely vegetated cells (to promote sedimentation of particles and flocculated bacteria) and open water cells (to promote the growth of algae). Because viruses are charged particles and respond to flocculants, at facilities that pretreat with septic tanks, most viruses become attached to the solids and remain in the tank septage.

CHAPTER 4
SURFACE FLOW WETLANDS

WETLAND DESIGN

Guidelines for designing a SF constructed wetland are given in table 5.

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. 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.

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

Table 5. Design summary for surface flow wetlands.

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

of cells 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. EPA's *Design Manual: Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment* (1988) and the Water Pollution Control Federation *Manual of Practice, Natural Systems for Wastewater Treatment* (1990) assume that the reduction of a specific water quality parameter, such as BOD_5, is a first order reaction and that concentration decreases exponentially with increasing retention time within the wetland.

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. In constructed wetlands, mixing characteristics are 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 under-designed.

BIOCHEMICAL OXYGEN DEMAND

The standard equation for BOD_5 removal for an unrestricted flow system (EPA 1988, Water Pollution Control Federation 1990) assumes that BOD_5 removal is described by a first-order model:

$$C_e/C_o = \exp(-K_T t) \qquad (4.1)$$

where

C_e = effluent BOD_5, mg/L

C_o = influent BOD_5, mg/L

K_T = temperature-dependent first-order reaction rate constant, days^{-1}

t = hydraulic residence time, days.

Flow through vegetated SF wetlands is complex and equation 4.1 must be modified to account for a number of the factors that affect flow through wetlands. Reed et al. (1994) suggest the following:

$$C_e/C_o = F \exp(-0.7 \cdot K_T \cdot A_v^{1.75} \cdot t \cdot \phi) \qquad (4.2)$$

where

F = fraction of BOD that does not settle in the headworks of the system

A_v = specific surface area for microbial activity, m^2/m^3

ϕ = void fraction.

The values to be used for K_T, F, A_V and ϕ in designing constructed wetlands for domestic wastewater have not been confirmed. A typical value that is often used for K_T at 20°C is 0.0057 days $^{-1}$ (EPA 1988). 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 experimenting with wetlands on a scale large enough to be appropriate. The wetland should be designed generously to accommodate these uncertainties.

The hydraulic residence time (t) can be represented by:

$$t = LWd/Q \qquad (4.3)$$

where

L = length
W = width
d = depth
Q = average flow rate [(flow in + flow out)/2]

The Water Pollution Control Federation (1990) recommends a minimum wetland area of about 28 to 37 ac per million gallons per day (mgd) of wastewater (3 to 4 ha/1000m³/day). A maximum BOD_5 loading rate of about 90 lb/ac/day (100 kg/ha/day) is recommended to help to prevent the occurrence of nuisance problems.

TOTAL SUSPENDED SOLIDS

Constructed wetlands are generally effective at reducing the concentration of TSS. Removal efficiencies are similar to those for BOD_5 and design for BOD_5 should accomplish similar TSS effluent levels. It is important to maintain shaded conditions with dense vegetation near the inflow and outflow to limit the growth of algae, which can add to TSS levels.

NITROGEN

Adequate HRT as influenced by hydraulic loading rate (HLR) and length-to-width ratio appears to be an important factor affecting TN removal efficiency, with lower removal efficiencies at HLRs greater than 3 inches/day (8 cm/day) and length-to-width ratios less than 2:1 (Water Pollution Control Federation 1990). Total nitrogen removal efficiency through nitrification/denitrification is temperature-dependent, with lowered removal efficiencies below about 48° F (10° C). Knight (1986) found no decrease in TN removal efficiency in a volunteer wetland at temperatures above 50° F (12° C). The Water Pollution Control Federation (1990) suggests that, to attain a TN removal efficiency of 50% or more, a minimum wetland area of about 37 ac per mgd of wastewater (4 ha/1000m³/day) should be provided.

CHAPTER 5
SUBSURFACE FLOW WETLANDS

INTRODUCTION

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 Mid-Atlantic states have provided operational data.

WETLAND DESIGN

Guidelines for designing a SSF wetland are given in table 6.

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.

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	Porous media 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. 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:

$$Q = k_s AS \tag{5.1}$$

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 ratio) 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 sized 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). Data from 14 SSF systems in the United States indicate that BOD_5 removal improves only slightly after 1 to 1.5 days HRT, up to an HRT of 7.5 days. The removal data for these systems can be reasonably approximated by a first order plug flow relationship up to about ±2 days. BOD_5 removal thereafter is limited and is believed to be influenced by the production of residual BOD_5 within the system. This is compatible with the hypothesis that BOD_5 is removed rapidly in the front part of wetland systems.

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 (HRT) factor in equation 4.1 can be defined as:

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

where

n = effective porosity of media (% as a decimal)

L = length of bed (ft, m)

W = width of bed (ft, m)

d = average depth of liquid in bed (ft, m)

Q = average flow through bed (ft^3/day, m^3/day).

The Q value in equation 5.2 is the average flow in the bed $[(Q_{in} + Q_{out})/2]$ to account for precipitation, seepage, evapotranspiration, and other gains and losses of water during transit in the bed. 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, as recommended previously, the design hydraulic gradient is limited to 10% of the potential available, 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 5.2 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, m^2)
other terms as defined previously.

The final 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 (A_s) 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 ($k_s \leq 1/3$ 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 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 these wetland systems export a BOD_5 residual due to decomposition of the natural organic detritus in the system.
8. In cold climates it is necessary to assume a design temperature for BOD_5 to first determine the required surface area. Thermal calculations are then necessary to determine winter heat losses and bed temperature conditions during the design HRT.

Further iterations of this procedure are necessary until the assumed temperature and the temperature determined by the heat loss calculations converge.

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 HRT 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.

REFERENCES

Bastian, R. K., and D. A. Hammer. 1993. The use of constructed wetlands for wastewater treatment and recycling. pp 59-68 *in* Constructed Wetlands for Water Quality Improvement, G. A. Moshiri (ed.). CRC Press, Boca Raton, FL.

Brix, H. 1993. Wastewater treatment in constructed wetlands: system design, removal processes, and treatment performance. pp 9-22 *in* Constructed Wetlands for Water Quality Improvement, G. A. Moshiri (ed.). CRC Press, Boca Raton, FL.

Center for Environmental Resource Management. 1993. Proceedings Subsurface Flow Constructed Wetlands Conference. University of Texas-El Paso, El Paso, TX. 306 pp.

Cooper, C.M., S. Testa, III, and S. S. Knight. 1993. Evaluation of ARS and SCS Constructed Wetland/Animal Waste Treatment Project at Hernando, Mississippi. National Sedimentation Laboratory Research Report No. 2, Oxford, MS. 55 pp.

Crumpton, W. G., T. M. Isenhart, and S. W. Fisher. 1993. Fate of non-point source loads in freshwater wetlands: results from experimental wetland mesocosms. pp 238-291 *in* Constructed Wetlands for Water Quality Improvement, G. A. Moshiri (ed.). CRC Press, Boca Raton, FL.

EC/EWPCA. 1990. European Design and Operations Guidelines for Reed Bed Treatment Systems. P. F. Cooper (ed.) Proceedings International Conference on the Use of Constructed Wetlands in Water Pollution Control. Pergamon Press, Oxford, U.K.

EPA (Environmental Protection Agency). 1988. Design Manual: Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment. EPA/625/1-88/022. Center for Environmental Research, Cincinnati, OH. 83 pp.

EPA (Environmental Protection Agency). 1993. Created and Natural Wetlands for Controlling Nonpoint Source Pollution. CRC Press, Boca Raton, FL. 216 pp.

Faulkner, S. P., and C. J. Richardson. 1989. Physical and chemical characteristics of freshwater wetland soils. pp 41-72 *in* Constructed Wetlands for Wastewater Treatment, D. A. Hammer (ed.). Lewis Publishers, Chelsea, MI.

Gambrel, R. P., and W. H. Patrick, Jr. 1978. Chemical and microbiological properties of anaerobic soils and sediments. *in* Plant Life in Anaerobic Environments, D. D. Hook and R. M. m. Crawford (eds.) Lewis Publishers, Chelsea, MI.

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

Hammer, D. A. 1992. Designing constructed wetland systems to treat agricultural nonpoint source pollution. Ecological Engineering 1:49-82.

Hey, D. L., K. R. Barrett, and C. Biegen. 1994. The hydrology of four experimental constructed marshes. Ecological Engineering 3:319-343.

Ives, M. 1988. Viral dynamics in artificial wetlands. pp 48-54 *in* G. A. Allen and R. A. Gearheart (eds.). Proceedings of a Conference on Wetlands for Wastewater Treatment and Resource Enhancement. August 2-4, Humboldt State University, Arcata, CA.

Kadlec. R. H. 1994. Detention and mixing in free water wetlands. Ecological Engineering 3:345-380.

Kadlec, R. H., W. Bastiaens, and D. T. Urban. 1993. Hydrological design of free water surface treatment wetlands. pp 77-86 *in* Constructed Wetlands for Water Quality Improvement, G. A. Moshiri (ed.). CRC Press, Boca Raton, FL.

Knight, R. L. 1986. Florida Effluent Wetlands - Total Nitrogen. CH2M HILL Wetland Tech. Ref. Doc. Ser., No 1.

Knight, R L., R. W. Ruble, R. H. Kadlec, and S.C. Reed. 1994. Wetlands Treatment Database (North American Wetlands for Water Quality Treatment Database). USEPA, Risk Reduction Engineering Laboratory, Cincinnati, OH. The database is available on 3.5" diskette, and requires DOS 3.3 or higher, 640K of memory, and 4MB of free disk space. To order, contact: Don Brown, USEPA (MS-347), Cincinnati, OH 45268; phone: (513) 569-7630; fax: (513) 569-7677; e-mail: brown.donald@epamail.epa.gov.

Mitsch, W. J., and J. G. Gosselink. 1986. Wetlands. Van Nostrand Reinhold, New York, NY. 539 pp.

Phipps, R. G., and W. G. Crumpton. 1994. Factors affecting nitrogen loss in experimental wetlands with different hydrologic loads. Ecological Engineering 3:399-408.

Reed, S. C. 1993. Design of Subsurface Flow Constructed Wetlands For Wastewater Treatment: a Technology Assessment. EPA 832-R-93-001. EPA Office of Wastewater Management, Washington, DC.

Reed, S., and D. S. Brown. 1992. Constructed wetland design - the first generation. Water Environment Research 64(6):776-781.

Reed, S., F. J. Middlebrooks, and R.W. Crites. 1994. Natural Systems for Waste Management and Treatment. 2nd ed. McGraw-Hill, New York.

Steiner, G. R., and R. J. Freeman, Jr. 1989. Configuration and substrate design considerations for constructed wetlands wastewater treatment. pp 363-377 *in* Constructed Wetlands for Wastewater Treatment, D. A. Hammer (ed.). Lewis Publishers, Chelsea, MI.

Watson, J. T., and J. A. Hobson. 1989. Hydraulic design considerations and control structures for constructed wetlands for wastewater treatment. pp 379-391 *in* Constructed Wetlands for Wastewater Treatment, D. A. Hammer (ed.). Lewis Publishers, Chelsea, MI.

Water Pollution Control Federation. 1990. Natural Systems for Wastewater Treatment. Manual of Practice FD-16, Chapter 9. Alexandria, VA.

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

For sale by the U.S. Government Printing Office
Superintendent of Documents, Mail Stop: SSOP, Washington, DC 20402-9328
ISBN 0-16-053000-8

ISBN 0-16-053000-8
90000
9 780160 530005