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Small and Decentralized Wastewater Management Systems

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CHAPTER 9

Wetlands and Aquatic Treatment Systems

Wetlands and aquatic treatment systems are those that use aquatic plants and animals for the treatment of municipal and industrial wastewater. Aquatic treatment covers a broad range of system types including a variety of constructed wetlands systems, floating aquatic plant systems, and combinations of both floating aquatic and wetland systems. The material to be presented is organized into sections dealing with: (1) types of and application of wetland and aquatic systems, (2) treatment kinetics in constructed wetlands and aquatic systems, (3) free-water-surface constructed wetlands, (4) subsurface-flow constructed wetlands, (5) floating aquatic plant systems using water hyacinth, (6) floating aquatic plant systems using duckweed, (7) combination systems, (8) design procedures for constructed wetlands and aquatic systems, (9) management of constructed wetlands and aquatic systems, and (10) emerging technologies.

9-1 TYPES OF AND APPLICATION OF WETLANDS AND AQUATIC SYSTEMS

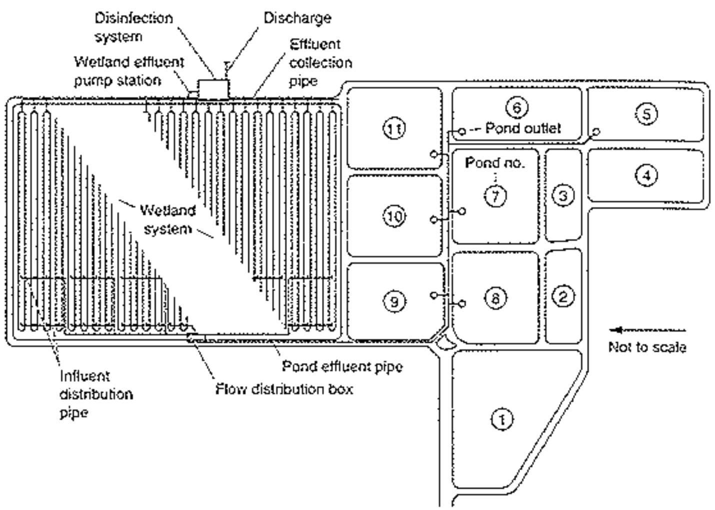
The principal types of wetlands and aquatic systems and their applications are introduced in this section. Aquatic systems that have been researched and demonstrated, but not applied in full-scale systems in the United States, are considered in Sec. 9-10, which deals with emerging technologies.

Types of Systems

The principal types of wetlands and aquatic treatment systems considered in this chapter include:

- Free-water-surface (FWS) constructed wetlands
- Subsurface-flow (SF) constructed wetlands
- Floating aquatic plant systems
- Combination systems

These systems, introduced in the following paragraphs, are considered separately in greater detail in Secs. 9-3 through 9-6.



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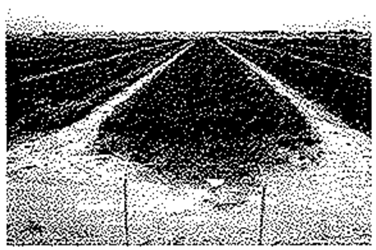
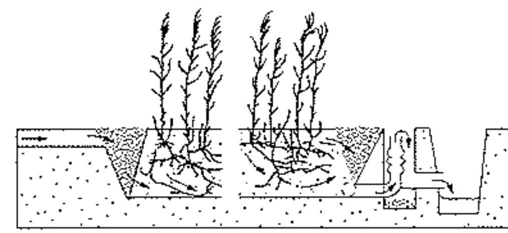


(b)

FIGURE 9-1
Free water surface (FWS) constructed wetland at Gustine, California: (a) definition sketch and (b) view of plug-flow channels.

Free-water-surface constructed wetlands. In a free-water-surface constructed wetland (marsh or swamp), the emergent vegetation is flooded to a depth that ranges from 4 to 18 in (100 to 450 mm). Typical vegetation for FWS systems includes cattails, reeds, sedges, and rushes. A FWS system consists typically of channels or basins with a natural or constructed impermeable barrier to prevent seepage. Some FWS systems are designed for complete retention of the applied wastewater through seepage and evapotranspiration. Wastewater is treated as it flows through the vegetation by attached bacteria and by physical and chemical processes. A typical free-water-surface constructed wetland at Gustine, California is shown in Fig. 9-1.

Subsurface-flow constructed wetlands. In a subsurface-flow constructed wetland (see Fig. 9-2) the wastewater is treated as it flows laterally through the porous medium. Emergent vegetation is planted in the medium, which ranges from coarse gravel to sand. The depth of the bed ranges from 1.5 to 3.3 ft (0.45 to 1 m) and the slope of the bed is typically 0 to 0.5 percent.



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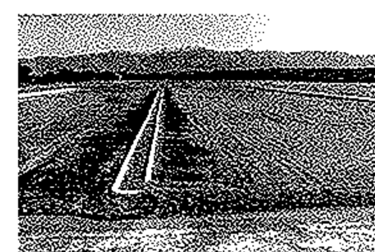
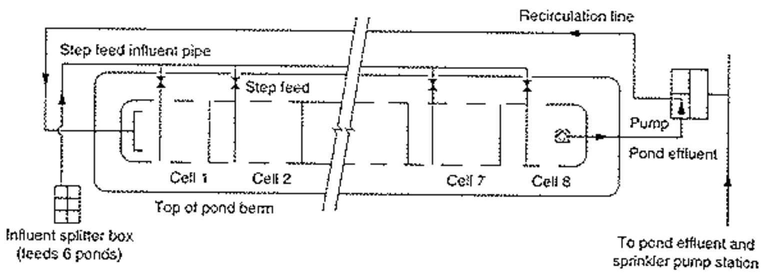


(b)

FIGURE 9-2
Typical SF constructed wetland: (a) definition sketch and (b) view of SF wetland at Mesquite, Nevada, before planting.



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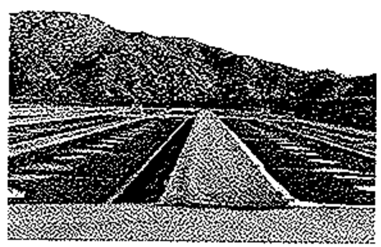


(b)

FIGURE 9-3
Floating plant aquatic treatment system at San Diego, California: (*a*) definition sketch for step-feed plug-flow channel with effluent recirculation to cell 1 (adapted from WCPH, 1996), and (*b*) view of water hyacinth system.

Floating aquatic plant systems. The two principal types of floating aquatic plant systems are the water hyacinth and duckweed systems (see Fig. 9-3). The water hyacinth (or similar plant) system involves floating or suspended plants with relatively long roots in ponds 2 to 4 ft (0.6 to 1.2 m) deep. The root structure serves as a medium for the attached growth of bacteria. The duckweed, on the other hand, has very short roots [usually less than 0.4 in (10 mm) long] and therefore functions as a surface shading system.

Combination systems. Aquatic and wetland systems can be used in combination, usually in series, to achieve specific water quality objectives. For example, a duckweed or hyacinth system could be used prior to a constructed wetland to minimize algae concentrations. A combined aerated aquatic treatment system with a constructed wetland has been studied for the treatment of septage at Harwich, Massachusetts (Nolte and Associates, 1989).

TABLE 9-1
Representative applications of constructed wetlands and aquatic treatment systems

Objective	Constituent removed/objective
Acid mine drainage	Metals and acidity
Advanced treatment	Nitrogen and phosphorus
Advanced treatment	Heavy metals and refractory organics
Combined secondary and advanced treatment	Organic matter (e.g., BOD_5), total suspended solids (TSS), pathogens, nitrogen, and phosphorus
Habitat development	Enhanced environmental resources
Irrigation return water	Nitrogen and phosphorus
Landfill leachate	Organic matter
Reclamation and water reuse	Organic matter, total suspended solids (TSS), and pathogens to restrictive standards (e.g., turbidity $\leq$ 2 NTU, SS $\leq$ 5 mg/L, and total coliform $\leq$ 2.2 organisms/100 mL)
Secondary treatment	Organic matter (e.g., BOD_5), total suspended solids (TSS), and pathogens
Septage treatment	Organic matter (e.g., BOD_5), total suspended solids (TSS), pathogens, nitrogen, and phosphorus
Stormwater treatment	Organic matter (e.g., BOD_5), total suspended solids (TSS), pathogens, nitrogen, phosphorus, and heavy metals and refractory organics

Application of Constructed Wetlands and Aquatic Systems

Constructed wetlands and aquatic systems have been used in a number of applications for the treatment of wastewaters with diverse characteristics. The principal types of applications are reported in Table 9-1. Three different applications, as discussed below, include tertiary treatment, stormwater treatment, and habitat development. However, as shown in Table 9-1, constructed wetlands have been used in a variety of other applications.

Sacramento County, California. The Sacramento Regional County Sanitation District operates the FWS constructed wetland shown in Fig. 9-4. The objectives of the project are to demonstrate advanced treatment for removal of metals, ammonia, and toxicity from the secondary effluent. The project results in the treatment of 1 Mgal/d (3785 m^3/d) on 15 ac (6.0 ha).

Stormwater wetlands. Wetlands for stormwater treatment and flow attenuation are becoming increasingly popular. An example of a stormwater wetlands is presented in Fig. 9-5.

Arcata, California. Wetlands at Arcata serve treatment, habitat enhancement, and educational benefits. The constructed wetland is used to treat 2.3 Mgal/d

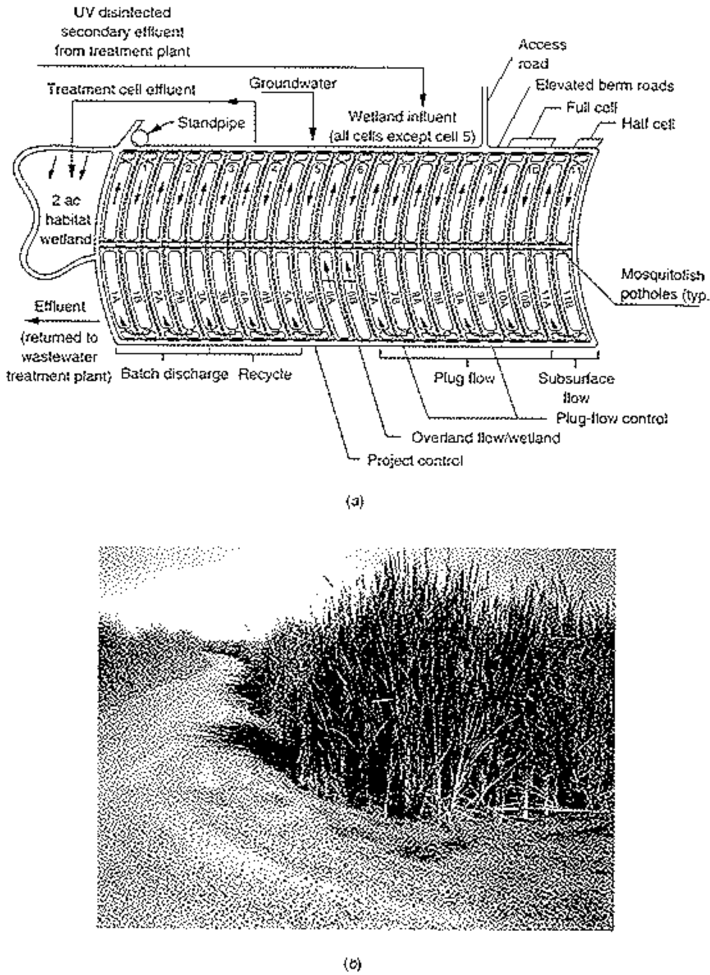


FIGURE 9-4
Sacramento Regional CSD Demonstration Wetland: (*a*) definition sketch and (*b*) view of the wetland.

(8.7 m^3/d) of effluent from a facultative lagoon. The effluent from the wetlands is then discharged into 31 ac (12.5 ha) of enhancement wetlands (marshes). The enhancement wetlands at Arcata feature a combination of 50 percent rooted vegetation and 50 percent open water (Gearheart and Finney, 1996). Views of the FWS wetlands at Arcata are shown in Fig. 9-6.

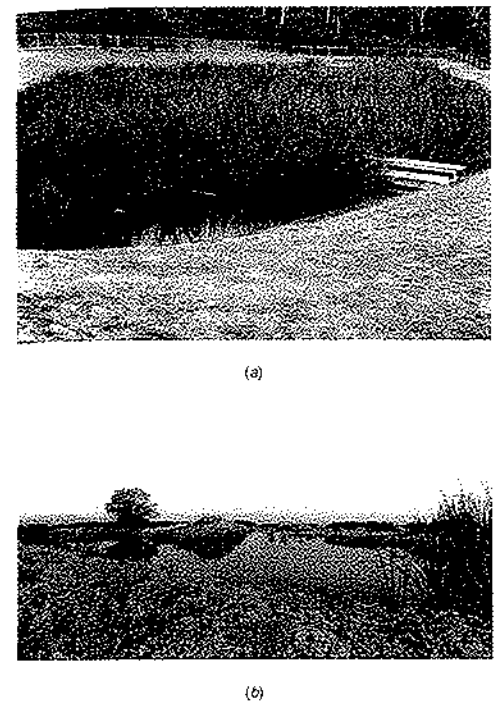


FIGURE 9-5
Typical views of constructed wetlands used for stormwater treatment: (*a*) small Australian system and (*b*) highway runoff system near Davis, California.

FIGURE 9-6
View of Arcata, California, FWS constructed wetlands.

9-2 TREATMENT KINETICS AND EFFLUENT VARIABILITY IN CONSTRUCTED WETLANDS AND AQUATIC SYSTEMS

Constituent removal mechanisms, constituent transformations, the types of reaction rates and their determination, the impact of plant decay, and the nature and variability of the effluent from constructed wetlands and aquatic systems are the topics considered in this section. The purpose is to provide a perspective for the analysis of the treatment performance of these systems, which are considered separately in Secs. 9-3 through 9-6. It will be apparent, after reading this section, that much additional information must be gathered and analyzed before the design of these systems can be considered scientific and routine.

Constituent Removal Mechanisms and Transformations

The principal removal and/or transformation mechanisms in various wetland systems are summarized in Table 9-2. Constituents considered are organic matter (e.g., BOD), suspended solids, nitrogen, phosphorus, metals, trace organics, and pathogens. An understanding of the removal mechanisms is of great importance in the development of models that can be used to predict process performance. As shown in Table 9-2, it is difficult to separate constituent removal and transformation processes, as both occur simultaneously in these systems. Definition of the removal mechanisms for individual constituents is complicated further because the constituent may be present in several forms, which will vary with the degree of treatment (e.g., soluble, colloidal, and particulate BOD and organic and ammonia nitrogen).

TABLE 9-2
Summary of principal removal and transformation mechanisms in constructed wetlands for the constituents of concern in wastewater

Constituent	Free water system	Subsurface flow	Floating aquatics
Biodegradable organics	Bioconversion by aerobic, facultative, and anaerobic bacteria on plant and debris surfaces of soluble BOD, adsorption, filtration, and sedimentation of particulate BOD	Bioconversion by facultative and anaerobic bacteria on plant and debris surfaces	Bioconversion by aerobic, facultative, and anaerobic bacteria on plant and debris surfaces
Suspended solids	Sedimentation, filtration	Filtration, sedimentation	Sedimentation, filtration
Nitrogen	Nitrification/denitrification, plant uptake, volatilization	Nitrification/denitrification, plant uptake, volatilization	Nitrification/denitrification, plant uptake, volatilization
Phosphorus	Sedimentation, plant uptake	Filtration, sedimentation, plant uptake	Sedimentation, plant uptake
Heavy metals	Adsorption of plant and debris surfaces, sedimentation	Adsorption of plant roots and debris surfaces, sedimentation	Adsorption of plant roots, sedimentation
Trace organics	Volatilization, adsorption, biodegradation	Adsorption, biodegradation	Volatilization, adsorption, biodegradation
Pathogens	Natural decay, predation, UV irradiation, sedimentation, excretion of antibiotics from roots of plants	Natural decay, predation, sedimentation, excretion of antibiotics from roots of plants	Natural decay, predation, sedimentation

Constituent transformations that occur in wetlands and aquatic systems are related to the carbon and nutrient cycles, considered previously in Chap. 2. In all wetlands and aquatic systems, both aerobic and anaerobic conditions occur to varying degrees at the same time. For example, the aerobic zone in FWS systems will usually be limited to the open water zones and a very limited upper portion of the water column. If the organic loading that is applied with the wastewater is large, the aerobic zone may extend for only a short distance into the water column. The development of an oxygen sag is quite common in FWS systems. Because both the aerobic and anaerobic conditions exist in FWS systems, both the aerobic and anaerobic carbon cycles are operative. Further, because the relative dominance of aerobic to anaerobic conditions will vary throughout the year, especially in northern climates, it is difficult to predict which cycle is dominant with respect to the treatment of organic material.

Volume- versus Area-Based Reaction Rates for the Removal of Constituents in Constructed Wetlands

In reviewing the constructed wetlands literature dealing with the removal of BOD, as well as other constituents, care must be taken to determine whether the rate constant is based on volume or on the surface area of the control volume. For example, with reference to Fig. 9-7, a volume-based removal-rate coefficient as proposed by Reed et al. (1995) will be given as follows. It should also be noted that in the following analysis it is assumed that the BOD is contributed from a single soluble constituent.

$$r_{BOD} = -k\text{BOD} \tag{9-1}$$

where r_{BOD} = rate of BOD loss per unit time per unit volume, $ML^{-3}T^{-1}$
k = rate coefficient for BOD removal, T^{-1}
BOD = carbonaceous BOD concentration, ML^{-3}

An area-based removal model has been proposed by Kadlec and Knight (1996):

$$r_{BOD} = -k_A(A/V)(\text{BOD}) = -(k_A/H)(\text{BOD}) \tag{9-2}$$

where r_{BOD} = rate of BOD loss per unit time per unit volume, $ML^{-3}T^{-1}$
k_A = rate coefficient for BOD removal, LT^{-1}
A = surface area, L^2
V = volume, L^3
BOD = carbonaceous BOD concentration, ML^{-3}
H = depth, L

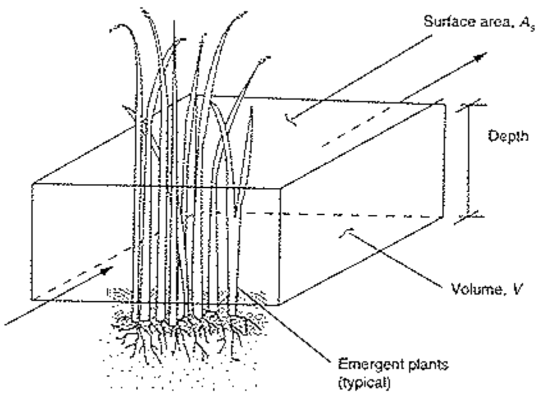


FIGURE 9-7
Definition sketch for modeling the removal of BOD and TSS in an FWS constructed wetland.

If the depth of the water in the wetlands does not change, then the two kinetic rate coefficients can be related directly. The difficulty in using either of the rate coefficients occurs when values developed for one water depth are applied to another depth. Further, neither coefficient is very reflective of all of the transformations occurring within the wetland. Clearly, the removal-rate constant for BOD must be related to the plant surface area below the water surface, and to the plant detrital material present in the wetland. More focused research needs to be done to determine how to model what is actually occurring with aggregate or lumped parameters in these systems. Because of the limited understanding of the actual removal mechanisms, the removal-rate coefficients now used for the design of constructed wetlands are *apparent* coefficients, and do not necessarily have any theoretical basis.

Actual (Nonideal) versus Ideal Flow in Constructed Wetlands

Ideal plug flow is typically assumed in the analysis and design of constructed wetlands. Unfortunately, it has been observed that plug-flow conditions seldom exist in the field. What normally occurs is that preferential-flow channels develop within the wetland as illustrated in Fig. 9-8. The nonideal flow conditions that occur in practice can be modeled (1) by using Eq. (3-13), developed for first-order kinetics and a plug-flow reactor with axial dispersion, and (2) by simulating the actual flow by using a number of complete-mix reactors in series. From dye measurements, it has been found that a cascade of four to six complete-mix reactors in series can be used to model the actual performance of constructed wetlands designed as plug-flow reactors. The impact of nonideal flow on the performance of an assumed plug-flow reactor is considered in Example 9-1.

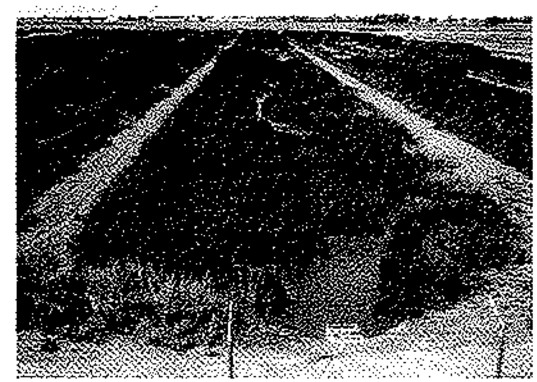


FIGURE 9-8
Typical example of preferential-flow channels that develop in FWS constructed wetlands, leading to axial dispersion.

EXAMPLE 9-1. ESTIMATE THE APPARENT REMOVAL-RATE CONSTANT FOR A FWS WETLAND. Estimate the apparent removal-rate constant for a FWS constructed wetland which takes into account axial dispersion. A plug-flow reactor has been designed with the following dimensions: width 200 ft, length 400 ft, and depth 1.25 ft. The flowrate is equal to 20,000 ft^3/d. Assume the first-order removal-rate constant for soluble BOD in the wetland, based on experiments conducted at a depth of 1.25 ft, is equal to 1.2 d^{-1}. If the influent soluble BOD value is equal to 300 mg/L, estimate the theoretical and actual BOD to be expected in the effluent, and the apparent removal-rate constants. Neglect the BOD contributed by the system constituents. The void ratio n (porosity) is 0.75.

Solution

1. Determine the theoretical detention time:

$$t = \frac{V}{Q} = \frac{ndA}{Q} = \frac{(0.75)(1.25\text{ ft})(200\text{ ft})(400\text{ ft})}{20,000\text{ ft}^3/\text{d}} = 3.75\text{ d}$$

2. Determine the theoretical effluent BOD from the plug-flow reactor assuming ideal plug flow:

$$\begin{aligned}\text{BOD}_{\text{eff}} &= \text{BOD}_{\text{inf}}e^{-kt}\\ &= 300e^{-1.2\times 3.75} = 3.3\text{ mg/L}\end{aligned}$$

3. Estimate the actual effluent BOD concentration. Assume the actual hydraulic performance of the constructed wetland can be modeled as a cascade of four equal-volume complete-mix reactors. Using Eq. (3-52), estimate the effluent BOD concentration from the plug-flow reactor.

$$\frac{C_4}{C_o} = \frac{1}{(1 + kV/4Q)^4}$$

where C_4 = effluent BOD concentration from the 4th reactor in series, mg/L
C_o = influent BOD concentration = 300 mg/L
k_o = overall BOD removal rate constant = 1.2 d^{-1}
V = total volume of wetland = 75,000 ft^3 (200 ft × 400 ft × 1.25 ft × 0.75)
4 = number of complete-mix reactors in series
Q = flow rate = 20,000 ft^3/d

Substituting and solving for C_4, which corresponds to the expected effluent BOD from the plug-flow reactor, yields

$$C_4 = \frac{300}{(1 + 1.2 \times 75{,}000)/(4 \times 20{,}000)^4} = 14.7 \text{ mg/L}$$

4. Determine the apparent BOD removal-rate constant, assuming a plug-flow model is used to estimate the effluent BOD from the wetland:

$$\frac{\text{BOD}_{\text{eff}}}{\text{BOD}_{\text{inf}}} = e^{-k_{\text{apparent}} \times t}$$

The detention time t is equal to 3.75 d [75,000 ft^3/(20,000 ft^3/d)]. Substituting the appropriate influent and effluent BOD values, the value of the apparent BOD removal-rate constant is

$$\frac{14.7}{300} = e^{-k_{\text{apparent}} \times 3.75}$$

$$\ln \frac{14.7}{300} = -3.016 = -k_{\text{apparent}} \times 3.75$$

$$k_{\text{apparent}} = 3.016/3.75 = 0.804 \text{ d}^{-1}$$

Comment. The above computations illustrate the importance of taking into account axial dispersion in constructed wetlands. Further, because of the limited data that are available in the literature, and the varying conditions that exist in constructed wetlands, the removal-rate constants for BOD and TSS currently used for the design of FWS constructed wetlands are apparent removal-rate constants.

Analysis of Constituent Removal-Rate Constants

The removal of wastewater constituents can be modeled mathematically as described in Chap. 2. Some of the problems encountered in developing models for constructed wetlands and aquatic systems are highlighted in the following discussion, especially with respect to the removal of BOD and TSS. Modeling BOD and TSS removal is complicated further because both are lumped constituents comprising multiple-size particles (see discussion in Chap. 2). For example, the kinetics involved in the removal of soluble and particulate BOD are quite different. Similarly, the mechanisms involved in the removal of settleable and colloidal suspended solids are quite different.

Modeling the removal of BOD. One of the difficulties encountered in modeling the removal of BOD in constructed wetlands and aquatic systems is that the influent BOD may be soluble, colloidal, and/or particulate. In addition, the removal can occur via aerobic/anoxic/anaerobic biological mechanisms and by flocculation/sedimentation. As a consequence, the value of the BOD removal-rate constant will depend on the distribution of the BOD between the three fractions. As reported in Table 2-10 in Chap. 2, the value of the BOD removal-rate constant can vary by a factor of 4 between particle sizes varying from 0.01 to 100 μm. In addition, aerobic and anoxic/anaerobic zones exist simultaneously in the wastewater column. Thus, the BOD removal-rate constants used in the design wetlands, as reported in the literature, are overall removal-rate constants, and should be modified to reflect the nature of the BOD in specific applications.

Another issue that occurs in modeling the removal of BOD in constructed wetlands, resulting from the presence of colloidal and/or particulate BOD composed of particles of varying size, is that the BOD removal-rate constant will vary as the wastewater passes through the wetland as illustrated in Fig. 3-12 in Chap. 3. As shown in Fig. 3-12, as the large particles are removed, by mechanisms such as flocculation/sedimentation, entrapment, and straining by chance contact, the removal-rate coefficient for the remaining smaller particles is reduced, even though the particles themselves may be easier to degrade. To account for the fact that the treatment response decreases as the most responsive constituents are removed, a retarded-rate expression should be used (see discussion in Chap. 3). The typical form of a retarded rate expression is

$$k = \frac{k_{\text{overall}}}{(1 + rt)^n} \tag{9-3}$$

where k = removal-rate constant at time t, 1/d
k_{overall} = initial overall removal-rate constant at time $t = 0$, 1/d
r = coefficient of retardation, 1/d
t = time, $t = L/v$
n = exponent related to the constituent being removed, unitless
L = length, ft
v = velocity, ft/d

When the r or n values are equal to zero, the value of k/k_o is equal to 1, and the overall removal-rate coefficient is constant. For example, the overall BOD removal-rate coefficient would be constant if all of the BOD were soluble or colloidal or particulate of a specified size. For this case, the value of the exponent n is equal to 0. For typical wastewater that contains soluble, colloidal, and particulate BOD, the value of the exponent n is approximately 1.0. For typical wastewater, the coefficient of retardation, which varies with plant density, is approximately equal to 0.2d^{-1}. Here again, sufficient data are not available in the literature that can be used to apply the retarded-removal-rate coefficient with confidence. The importance of the coefficient of retardation will depend on the distribution of the BOD components between the soluble, colloidal, and suspended fractions.

Modeling the removal of TSS. From the above discussion, it is clear that a retarded removal-rate coefficient should be used for modeling the removal of TSS.

The TSS modeling problem is further complicated because of the flocculation of particles that can occur anywhere within the wetland, which increases locally the overall removal-rate constant. In most wetlands, the removal-rate coefficient for TSS is continually changing as the wastewater flows through the wetland. The estimation of TSS removal is illustrated in Example 9-2.

EXAMPLE 9-2. ESTIMATE THE TSS REMOVAL IN A FWS WETLAND. Estimate the removal of TSS in the plug-flow reactor considered in Example 9-1 (width 200 ft, length 400 ft, and depth 1.25 ft). The flowrate is equal to 20,000 ft^3/d. Assume the overall first-order removal-rate constant for TSS in the wetland is equal to 1.25/d. If the influent TSS value is equal to 160 mg/L, estimate the actual TSS to be expected in the effluent, assuming the coefficient of retardation is equal to 0.2 d^{-1}. Compare the TSS effluent value with retardation to the corresponding value without retardation. Assume no flocculation occurs in the wetland, and that the void ratio is 0.75.

Solution

1. Estimate the actual effluent TSS concentration. Assume the actual hydraulic performance of the constructed wetland can be modeled as a cascade of four equal-volume complete-mix reactors. Combining Eqs. (3-52) and (9-3), estimate the effluent TSS concentration from the plug-flow reactor.

$$\frac{TSS_4}{TSS_o} = \frac{1}{\left(1 + \dfrac{k_o}{1+rt} \times \dfrac{V}{4Q}\right)^4} = \frac{1}{\left(1 + \dfrac{0.25 k_o t}{1+rt}\right)^4}$$

where TSS_4 = effluent TSS concentration from the fourth reactor in series, mg/L
TSS_o = influent TSS concentration = 160 mg/L
k_o = unretarded overall TSS removal-rate constant = 1.25 d^{-1}.
r = coefficient of retardation, 0.2 d^{-1}
t = detention time, d = $V/Q = ndA/Q$
V = total volume of wetland = 75,000 ft^3
4 = number of complete-mix reactors in series
Q = flowrate = 20,000 ft^3/d

Substituting and solving for TSS_4 which corresponds to the expected effluent TSS from the plug-flow reactor, yields:

$$\frac{TSS_4}{TSS_o} = \frac{1}{\left[1 + \dfrac{0.25 \times 1.25 \times 3.75}{1 + (0.2 \times 3.75)}\right]^4} = 20.6 \text{ mg/L}$$

2. Estimate the effluent TSS concentration without retardation:

$$TSS_4 = \frac{160}{[1 + (0.25 \times 1.25 \times 3.75)]^4} = 7.2 \text{ mg/L}$$

Comment. The importance of taking into account both axial dispersion and retardation in constructed wetlands is clearly illustrated in this example. The first-order removal-rate constant was assumed for purposes of illustrating the concept.

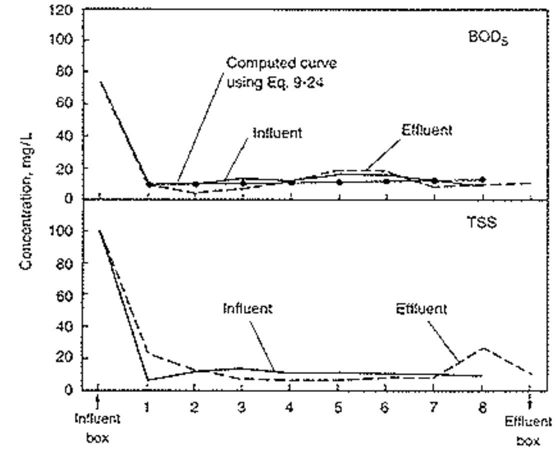


FIGURE 9-9
Removal of BOD and TSS with distance, in water hyacinth treatment system at Aqua III in San Diego, CA (detention time = 6.4 d).

Impact of detention time on observed removal-rate constants for BOD and TSS. Another observation that has been made in a number of wetlands and aquatic systems is that both BOD and TSS are removed extremely rapidly near the influent end of the constructed wetland or aquatic system. Data for the removal of BOD with distance in one of the plug-flow water hyacinth ponds at the San Diego aquaculture project are shown in Fig. 9-9 (WCPH, 1996). The key finding at San Diego was that, under aerobic conditions, secondary treatment was attained within the first 50 ft, and that the remaining 350 ft of the pond provided minimal treatment, if any. This finding led to the development of a pond operating system which incorporated step feed with effluent recycle, as discussed in Sec. 9-5.

If, for practical purposes, the BOD removal during the first 50 ft is modeled as a first-order function (Eq. 3-4), then the apparent removal-rate constant for the first segment of the plug-flow reactor (detention time = 0.8 d) would be

$$\ln\left[\frac{C}{C_o}\right] = k_{apparent} \times t$$

$$\ln\left[\frac{29}{140}\right] = k_{apparent} \times 0.8 \text{ d}$$

$$k_{apparent} = 1.97 \text{ d}^{-1}$$

If, on the other hand, the effluent value from the entire plug-flow pond had been used in the analysis, the corresponding value of the apparent removal-rate constant would be

$$\ln\left[\frac{12}{140}\right] = k_{\text{apparent}} \times 6.4 \text{ d}$$

$$k_{\text{apparent}} = 0.38 \text{ d}^{-1}$$

The difference between these values is significant. This type of problem pervades most of the information reported in the literature on constructed wetlands, where only input and output values are used in determining the apparent removal-rate constant, especially where varying factors of safety have been incorporated into the design of the system.

Effect of temperature. It is also instructive to consider the effect of temperature in the above situations. Bacterial activity responsible for BOD removal is temperature-dependent, with θ values for constructed wetlands ranging from 1.02 to 1.06. It has been observed that bacterial populations in natural systems can acclimate to colder temperatures and maintain their mass in spite of slower activity rates (Vela, 1974). With lower temperatures, the removal of influent BOD occurs farther down the wetland than when water temperatures are higher. In constructed wetlands with excessive detention times, the effect of temperature on BOD and TSS removal will not be observed, as illustrated below.

If it is assumed that the wastewater temperature is 10°C and the temperature coefficient is 1.06, then, from Eq. (3-22) the value of the two removal-rate coefficients, determined above, would be

$$\frac{k_2}{k_1} = \theta^{(T_2 - T_1)}$$

$$\frac{k_2}{1.97/\text{d}} = 1.06^{(10-20)} \qquad k_2 = 1.10 \text{ d}^{-1}$$

$$\frac{k_2}{0.38/\text{d}} = 1.06^{(10-20)} \qquad k_2 = 0.21 \text{ d}^{-1}$$

In the first case, a value of 29 mg/L will be reached after 1.43 d. A value of 12 mg/L, corresponding to the effluent value observed during the summer, would have been reached during the cold period in 2.23 d.

$$\ln\left[\frac{29}{140}\right] = -1.10 \times t$$

$$t = 1.43 \text{ d}$$

$$\ln\left[\frac{12}{140}\right] = -1.10 \times t$$

$$t = 2.23 \text{ d}$$

The implications of this simple analysis are also significant. For example, if the effluent from the plug-flow pond (detention time = 6.4 d) were sampled during the period when the wastewater temperature was 10° C, it would be concluded that temperature has no effect on the process. As with the BOD analysis, temperature effects are often misinterpreted when only input and output values are used in the analysis. This situation is especially problematic when effluent values from overdesigned systems are used. In addition, the input and output values used for the determination of the temperature effects are confounded statistically, because they also include the effects of natural variation. This situation is considered subsequently in the discussion dealing with the selection of design values for BOD that take variability into account.

Modeling the removal of other wastewater constituents. For practical purposes, the modeling of the removal of nitrogen in constructed wetlands is accomplished by assuming that the organic nitrogen in the influent will convert into the form of ammonia nitrogen. Use of the temperature correction factor to adjust the removal-rate coefficient for nitrogen is also appropriate, because both nitrification and denitrification are highly temperature-sensitive. A similar approach is often used for other constituents that may be lumped (or have distributed parameters).

Impact of Vegetation Decay in Wetlands and Aquatic Systems

An important characteristic of both natural and constructed wetlands, especially the free-water-surface type, is related to the growth and the short- and long-term impact of the decay of plant vegetation in these systems. When plant mass dies back and is submerged in water, water-soluble organic substances are transferred to the liquid by leaching. The leached material consists primarily of amino acids, sugars, and nonvolatile and volatile aliphatic acids. In general, these materials are readily metabolized within the wetland (Westermann, 1993). Further (long-term) degradation of the plant material in the system will depend on the ratios of the major polymers (lignin, cellulose, and hemicellulose) in the thatch layer, the structure of the lignocellulose, and the physicochemical character of the wetland (see Westermann, 1993).

The importance of this discussion is that, in constructed wetlands, as well as in aquatic treatment systems, it has been observed that the effluent from such systems will contain varying concentrations of organic matter, without the application of wastewater. Typical concentration values for the organic material in the effluent, expressed in terms of BOD, are in the range from 2 to 10 mg/L, with typical values from 3 to 5 mg/L. This effluent value has often led to the formulation of BOD removal models on the false premise that the effluent BOD is residual influent BOD (see discussion of BOD in Sec. 2-1, Chap. 2).

Composition of Effluent BOD

The BOD in the effluent from constructed wetlands and aquatic systems is composed of the BOD resulting from plant decay, as discussed above, and the residual BOD remaining from the original influent BOD. As noted in Sec. 2-1 in Chap. 2, the residual BOD derived from the influent BOD will typically comprise cell tissue and cell fragments, especially in systems with long detention times. The total BOD in the effluent is given by

$$BOD_{ECW} = BOD_{PD} + BOD_{RIW} \tag{9-4}$$

where BOD_{ECW} = effluent BOD from constructed wetland, mg/L
BOD_{PD} = BOD resulting from plant decay, mg/L
BOD_{RIW} = residual BOD from influent wastewater, mg/L

Because both BOD_{PD} and BOD_{RIW} have been observed to vary throughout the year, this variability must be considered in the design of constructed wetlands and aquatic systems. At present, limited data are available on the variability of the plant decay contribution (BOD_{PD}) with season. What data are available are contradictory. In some systems, the BOD contribution from plant decay increases during the summer, whereas in other systems it increases during the winter. For this reason, it is recommended that a typical value be used for estimating BOD_{PD} until more information becomes available.

Design of Constructed Wetlands Taking into Account Variability

As noted in Chap. 3 (Sec. 3-7), because of the variations observed in effluent quality, a treatment process should be designed to produce an average effluent concentration below the permit requirements. In Eq. (9-4), the effluent BOD (BOD_{RIW}) value reflects the effects of temperature, axial dispersion, and natural process variability. Because most of the effluent BOD data that have been collected to date are confounded statistically, the variability due to axial dispersion versus temperature versus natural causes is unknown. The variability of BOD_{RIW} including the combined effects of axial dispersion, temperature, and natural variability can be assessed by analyzing the long-term average monthly performance data from operating systems using the coefficient of reliability as outlined in Chap. 3. Typical values for the coefficient of variation for the different types of wetlands subject to different temperature ranges

TABLE 9-3
Typical coefficients of variation for constructed wetlands subject to different wastewater temperature variations*

		Coefficient of variation V_x for removal of	
Type of wetland	Temperature range, °C	BOD	TSS
Free water surface	5–20	0.40–0.65	0.30–0.50
	10–25	0.25–0.40	0.20–0.40
Subsurface flow	5–20	0.25–0.30	0.25–0.50
	10–25	0.25–0.40	0.20–0.40
Water hyacinths	10–20	0.20–0.25	0.20–0.25
	15–25	0.15–0.20	0.15–0.25

*The data presented in this table should be used with caution, as there is great variability in the performance of these systems.

are given in Table 9-3. The determination of the BOD design value for a constructed wetland is illustrated in Example 9-3.

EXAMPLE 9-3. DETERMINE THE EFFLUENT BOD DESIGN CONCENTRATION VALUE TAKING INTO ACCOUNT THE VARIABILITY IN THE PERFORMANCE OF A CONSTRUCTED WETLAND. Using the following average monthly effluent BOD data from the Ouray, Colorado, FWS constructed wetland wastewater treatment facility, determine the coefficient of reliability and the appropriate BOD design value, if the effluent from a similar treatment facility is to be equal to or less than 30 mg/L 90 percent of the time.

	BOD, mg/L	
Month	1994	1995
January	10	12
February	10	8
March	11	7
April	14	9
May	19	8
June	19	15
July	24	14
August	24	10
September	15	18
October	12	16
November	1	6
December	11	3

Solution

1. Use the coefficient of reliability approach introduced in Sec. 3-7 in Chap. 3 to determine the appropriate design value.

2. Determine the statistics for the given data using a standard statistical package.

Parameter	Value
Minimum	1
Maximum	24
Sum	296
Points	24
Mean	12.3
Median	11.5
RMS	13.6
Standard deviation	5.8
Variance	33.9
Standard error	1.2
Skewness	0.3
Kurtosis	−0.2

3. Determine the coefficient of reliability using Eq. (4-23):

$$COR = (V_x^2 + 1)^{1/2} \times \exp\left\{-Z_{1-\alpha}\left[\ln\left(V_x^2 + 1\right)\right]^{1/2}\right\}$$

a. Determine the value of V_x using the results of the statistical analysis:

$$V_x = \frac{\sigma_x}{m_x} = \frac{5.8}{12.3} = 0.472$$

b. The value of $Z_{1-\alpha}$ for a cumulative probability of 90 percent from Table 4-24 is 1.282.

c. Determine the coefficient of reliability:

$$\text{COR} = (0.472^2 + 1)^{1/2} \times \exp\left\{ -1.282\left[\ln\left(0.472^2 + 1\right)\right]^{1/2} \right\} = 0.622$$

4. Determine the appropriate design value for BOD. Using Eq. (4-22) and the COR value determined in step 3, the design value is

$$m_x = (\text{COR})X_s = 0.622 \times 30 \text{ mg/L} = 18.7 \text{ mg/L}$$

Comment. As the variability in the effluent quality increases, the COR value becomes smaller, and a more conservative design value must be used to achieve the proposed level of treatment.

9-3 FREE-WATER-SURFACE CONSTRUCTED WETLANDS

The use of constructed wetlands with water levels above the ground surface has ranged from achieving secondary treatment, to polishing of secondary effluent, to providing wildlife habitat and reuse of the water. The material presented in this section deals with a description of the process, constituent removal and transformation mechanisms, process performance, and process design considerations. General design considerations and the management for these systems are discussed on Secs. 9-8 and 9-9, respectively.

Process Description

A free-water-surface (FWS) system consists typically of channels or basins with a natural or constructed impermeable barrier to prevent seepage. Plants in free-water-surface constructed wetlands serve a number of purposes. Stems, submerged leaves, and litter serve as support media for the growth of attached bacteria. Leaves above the water surface shade the water and reduce the potential for algal growth. Oxygen is transported from the leaves down into the root zone, which supports the plant growth. A limited amount of oxygen may leak out of the submerged stems to support attached bacterial growth. Pretreatment for FWS wetlands usually consists of settling (septic tanks or Imhoff tanks), screening with a rotary disk filter, or stabilization lagoons. Because the major sources of oxygen are surface reaeration in open water from the atmosphere and attached-growth algae, the BOD loading generally needs to be kept below 100 lb/ac·d.

TABLE 9-4
Typical characteristics of emergent plants used in constructed wetlands

Common name	Scientific name	Temperature, °C		pH range for effectiveness	Maximum salinity tolerance, ppt
		Desirable	Seed germination		
Bulrush	*Scirpus* spp.	16–27		4–9	20
Cattail	*Typha latifolia*	10–30	12–24	4–10	30
Common arrowhead	*Sagittaria latifolia*				
Common reed	*Phragmites australis*	12–23	10–30	2–8	45
Rush	*Juncus* spp.	16–26		5–7.5	20
Sedge	*Carex* spp.	14–32		5–7.5	
Yellow flag	*Iris pseudacorus*				

Source: Stephenson et al. (1980)
Note: ppt = parts per thousand

Site selection. Site features for potential FWS sites are similar to those for wastewater treatment ponds. Slopes of 0 to 3 percent are most favorable. Soils should be slowly permeable. Compacted clay or synthetic liners may be required to limit percolation. Groundwater levels can be relatively high without causing any concern because percolation is restricted or eliminated.

Vegetation types. Emergent plants most frequently used in FWS include: cattails, bulrush, reeds, arrowhead, and sedges. Characteristics of these plants are summarized in Table 9-4 (Stephenson et al., 1980). More details on emergent plants are available in the reference works by Mitsch and Gosselink (1993) and Hammer (1992). In addition to the plants listed in Table 9-4, arrow arum (*Peltandra* spp.) and pickerelweed (*Pontederia* spp.) have been used in constructed wetlands. Other locally grown emergent vegetation can also be considered.

Constituent Removal and Transformation Mechanisms

High removals of BOD and TSS can be expected from FWS wetlands, along with significant removals of nitrogen, metals, trace organics, and pathogens. The degree of removal usually is dependent on detention time and temperature. The operative removal mechanisms for FWS constructed wetlands are described below.

BOD removal. Soluble and particulate BOD are removed by different mechanisms in FWS constructed wetlands. Soluble BOD is removed by biological activity and adsorption on the plant and detritus surfaces and in the water column. The low velocities and emergent plants facilitate flocculation/sedimentation and entrapment of the particulate BOD. Organic solids, removed by sedimentation and filtration, as discussed below, will exert an oxygen demand, as does the decaying vegetation. As a result, the influent BOD is removed rapidly with length down the wetland cell. The observed BOD in the wetland will also reflect the detrital and benthic demand, which leads to a "background" concentration.

Total suspended solids removal. The principal removal mechanisms for TSS are flocculation and sedimentation in the bulk liquid, and filtration (mechanical straining, chance contact, impaction, and interception) in the interstices of the detritus. Most of the settleable solids are removed within 50 to 100 ft of the inlet. Optimal removal of TSS requires a full stand of vegetation to facilitate sedimentation and filtration and to avoid regrowth of algae. Algal solids may take 6 to 10 d of detention time for removal.

Nitrogen removal. Nitrogen removal in constructed wetlands is accomplished by nitrification and denitrification. Plant uptake accounts for only about 10 percent of the nitrogen removal. Nitrification and denitrification are microbial reactions that depend on temperature and detention time. Nitrifying organisms require oxygen and an adequate surface area to grow on and, therefore, are not present in significant numbers in either heavily loaded systems (BOD loading > 100 lb/ac·d) or in newly constructed systems with incomplete plant cover. On the basis of field experience with FWS systems, one to two growing seasons may be needed to develop sufficient vegetation to support microbial nitrification. Denitrification requires adequate organic matter (plant litter or straw) to convert nitrate to nitrogen gas. The reducing conditions in mature FWS constructed wetlands resulting from flooding are conducive to denitrification. If nitrified wastewater is applied to a FWS wetland, the nitrate will be denitrified within a few days of detention.

Phosphorus removal. The principal removal mechanisms for phosphorus in FWS systems are adsorption, chemical precipitation, and plant uptake. Plant uptake of inorganic phosphorus is rapid; however, as plants die, they release phosphorus, so that long-term removal is low. Phosphorus removal depends on soil interaction and detention time. In systems with zero discharge or very long detention times, phosphorus will be retained in the soil or root zone. In flow-through wetlands with detention times between 5 and 10 d, phosphorus removal will seldom exceed 1 to 3 mg/L. Depending on environmental conditions within the wetland, phosphorus, as well as some other constituents, can be released during certain times of the year, usually in response to changed conditions within the system such as a change in the oxidation-reduction potential (ORP).

Metals removal. Heavy metal removal is expected to be very similar to that of phosphorus removal, although limited data are available on actual removal mechanisms. The removal mechanisms include adsorption, sedimentation, chemical precipitation, and plant uptake. As with phosphorus, metals can be released during certain times of the year, usually in response to change in the oxidation-reduction potential within the system.

Trace organics removal. Although limited data are available on removal of trace organics, the FWS process is similar to overland flow (see Chap. 10) where removals of 88 to 99 percent have been reported (Reed et al., 1995). Removal mechanisms include volatilization, adsorption, and biodegradation.

Pathogen removal. Pathogenic bacteria and viruses are removed in constructed wetlands by adsorption, sedimentation, predation, and die-off from exposure to sunlight (UV) and unfavorable temperatures.

Process Performance

The performance expectations for FWS constructed wetlands are presented in Tables 9-5 through 9-8. Performance depends, of course, on design criteria, wastewater characteristics, and operations.

BOD and TSS removal. Operating data from a number of FWS constructed wetlands for removal of BOD and TSS are presented in Table 9-5. Removals are

TABLE 9-5
Typical BOD and TSS removals observed in FWS constructed wetlands

	BOD, mg/L		TSS, mg/L		
Location	Influent	Effluent	Influent	Effluent	Reference
Arcata, California	26	12	30	14	Gearheart et al., 1989
Benton, Kentucky	25.6	9.7	57.4	10.7	U.S. EPA, 1993
Cannon Beach, Oregon	26.8	5.4	45.2	8.0	U.S. EPA, 1993
Ft. Deposit, Alabama	32.8	6.9	91.2	12.6	U.S. EPA, 1993
Gustine, California	75	19	102	31	Crites, 1996
Iselin, Pennsylvania	140	17	380	53	Watson et al., 1979
Listowel, Ontario	56.3	9.6	111	8	Herskowitz et al., 1987
Ouray, Colorado	63	11	86	14	Andrews, 1996
West Jackson Co., Mississippi	25.9	7.4	40.4	14.1	U.S. EPA, 1993
Sacramento Co., California	23.9	6.5	8.9	12.2	Nolte and Associates, 1997

TABLE 9-6
Typical ammonia and nitrogen removals observed in FWS constructed wetlands

Location	Type of effluent	Ammonia, mg/L		Total nitrogen, mg/L	
		Influent	Effluent	Influent	Effluent
Arcata, California[*]	Oxidation pond	12.8	10		11.6
Iselin, Pennsylvania[†]	Oxidation pond	30	13		
Jackson Bottoms, Oregon	Secondary	9.9	3.1		
Listowel, Ontario[‡]	Primary	8.6	6.1	19.1	8.9
Pembroke, Kentucky	Secondary	13.8	3.35		
Sacramento Co., California[§]	Secondary	14.1	7.2	16.8	9.1

[*]Full-scale operation from August 1986 to May 1988 (Gearheart et al., 1989).
[†]Full-scale operation from March 1983 to September 1985 (Watson et al., 1987).
[‡]System 4, pilot operation from 1980 to 1984 (Herskowitz et al., 1987).
[§]Demonstration wetland, May 1995 to November 1995.

TABLE 9-7
Removal of metals in constructed wetlands at Sacramento Regional County Sanitation District[*]

Metal	Average total recoverable concentration, μg/L	
	Influent	Effluent
Antimony (Sb)	0.43	0.19
Arsenic (As)	1.75[†]	2.38
Cadmium (Cd)	0.10	0.07
Chromium (Cr)	1.05	1.32
Copper (Cu)	8.90	4.14
Lead (Pb)	0.85	0.25
Mercury (Hg)	11.39 ng/L[‡]	4.57 ng/L[‡]
Nickel (Ni)	6.85	8.34
Silver (Ag)	0.34	0.05
Zinc (Zn)	37.0	7.4

[*]Results for the period July 1996 to December 1996 (Nolte and Associates, 1997). The system began receiving treated wastewater in May 1994.
[†]Arsenic in the influent dropped from 2.63 μg/L in 1995 to 1.75 μg/L in 1996.
[‡]ng/L = nanograms per liter.

TABLE 9-8
Removal of fecal coliform in FWS constructed wetland systems

Location	Unit	Influent	Effluent[*]	Detention time, d
Iselin, Pennsylvania: cattails and grasses[†]				
Winter season (Nov.–April)	No./100 mL	1.7×10^6	4.3×10^3	6
Summer season (May–Oct.)	No./100 mL	1.0×10^6	723	6
Arcata, California; bulrush wetland[‡]				
Winter season (Nov.–April)	No./100 mL	4.3×10^3	900	1.9
Summer season (May–Oct.)	No./100 mL	1.8×10^3	80	1.9
Listowel, Ontario; cattails[‡]				
Winter season (Nov.–April)	No./100 mL	5.56×10^5	1.4×10^3	7–14
Summer season (May–Oct.)	No./100 mL	1.98×10^5	400	7–14

[*]Undisinfected.
[†]Sand bed, subsurface flow.
[‡]Free water surface.

typically 60 to 80 percent for BOD and 50 to 90 percent for TSS (depending on the nature and concentration of the influent TSS).

Ammonia removal. As shown in Table 9-6, the degree of nitrification in FWS systems is relatively incomplete, ranging from 25 percent in Arcata to 56 percent at Iselin. The data should not be construed as indicating that nitrification cannot be complete in FWS constructed wetlands, because nitrification has not been required generally in effluent permit limitations. Most of the systems that have been monitored were designed for BOD and TSS removal with detention times between 5 and 10 d. At Sacramento County, seasonal nitrification has averaged 75 percent for a detention time of 10 d (Crites et al., 1997).

Nitrogen removal. Nitrogen removal is limited by the ability of the FWS system to nitrify. When nitrogen is present in the nitrate form, nitrogen removal is generally rapid and complete. The removal of nitrate depends on the concentration of nitrate, the detention time, and the available organic matter. Because the water column is nearly anoxic in many wetlands treating municipal wastewater, the reduction of nitrate will occur within a few days. At Sacramento County, the nitrate does not accumulate as the ammonia is nitrified. Nitrate-nitrogen concentrations average 0.44 mg/L and range from 0.08 mg/L in the summer to 0.94 mg/L in the spring (Nolte and Associates, 1997).

Phosphorus removal. Phosphorus removal in wetlands depends on the loading rate and the detention time. Because plants take up phosphorus over the growing season and then release some of it during senescence, reported removal data must be questioned as to when the system was sampled and how long the system had been in operation. At Sacramento County, the typical spring/summer uptake of phosphorus is about 0.5 mg/L, resulting in an annual removal of 14 percent (Nolte and Associates, 1997).

TABLE 9-9
Typical design criteria and expected effluent quality for FWS constructed wetlands

Item	Unit	Value
Design parameter		
Detention time	d	2–5 (BOD) 7–14 (N)
BOD loading rate	lb/ac·d	<100
Water depth	ft	0.2–1.5
Minimum size	ac/Mgal·d	5–10
Aspect ratio		2:1 to 4:1
Mosquito control		Required
Harvesting interval	yr	3–5
Expected effluent quality*		
BOD_5	mg/L	<20
TSS	mg/L	<20
TN	mg/L	<10
TP	mg/L	<5

*Expected effluent quality based on a BOD loading equal to or less than 100 lb/ac·d and typical settled municipal wastewater.

Metals removal. Metals removal depends on detention time, influent metal concentrations, and metal speciation. Removal data for heavy metals in the Sacramento County Demonstration Wetlands are presented in Table 9-7.

Pathogen removal. Fecal coliform removals of 99.9 percent (3 log reduction) have been reported at Iselin, Pennsylvania, and at Listowel, Ontario (Watson et al., 1989). Virus removal at Arcata, California, ranged from 90 to 99 percent (Gersberg et al., 1989). Removals of pathogen indicator organisms are presented in Table 9-8.

Process Design Considerations

The principal process design criteria for FWS constructed wetlands are detention time, organic loading rate, required surface area, and water depth. Hydraulic loading rate is a common basis of comparison, either in in/d or ac/Mgal·d, but both rates are calculated from the area and the flow. Other design considerations include aspect (length-to-width) ratio, hydraulic considerations, thermal considerations, and vegetation harvesting. Typical process design criteria are presented in Table 9-9.

Detention time for BOD. The required detention time, taking into account axial dispersion and temperature effects, can be determined theoretically by

$$t = \frac{V}{Q} = \left[\frac{1}{(C_n/C_o)^{1/n}} - 1\right] \times \frac{n}{k_o} \qquad (9\text{-}5)$$

where t = detention time for BOD removal, d
V = total volume of wetland, ft^3 (gal)
Q = flowrate, ft^3/d (gal/d)
C_n = effluent BOD concentration from the nth reactor in series, mg/L
C_o = influent BOD concentration, mg/L
n = number of complete-mix reactors in series
k_o = overall BOD removal-rate constant, corrected for temperature, 1/d

The value of C_n is the residual BOD value from the influent BOD. The actual total BOD concentration in the effluent consists of the residual BOD value from the influent BOD plus the BOD from plant decay. Typically, four reactors in series are used most commonly to account for axial dispersion in plug-flow reactors. The value of k_o is usually based on controlled pilot-scale experiments in which axial dispersion is not an issue.

Because insufficient data are available to determine the overall removal rate constant k_o or COR values, it is recommended that the apparent k factor in Eq. (9-6) be used for design. Derived from field observations, the empirical temperature-corrected apparent BOD removal-rate constant $k_{apparent}$ is 0.678 d^{-1}. It should be noted that Eqs. (9-5) and (9-6) will yield approximately the same answer, if k = 1.01 d^{-1} for Eq. (9-5), because apparent removal-rate constants are derived from systems with varying amounts of axial dispersion.

$$t = -\frac{\ln C/C_o}{k_{apparent}} \qquad (9\text{-}6)$$

If adequate statistical data are available for similar systems in similar climatic conditions, the design detention time can be computed by using the coefficient of reliability concept as outlined in Chap. 3. The BOD design value for the wetland is

$$BOD_{DES} = BOD_{RIW} \times (COR) \qquad (9\text{-}7)$$

where BOD_{RIW} = residual average monthly BOD from influent wastewater, mg/L, and COR = coefficient of reliability (see Sec. 3-7 in Chap. 3 and Example 9-2).

Organic loading rate. As a general rule, the organic loading rate (OLR) should not exceed 100 lb BOD/ac·d (110 kg BOD/ha·d), if aerobic conditions near the water surface are to be maintained and odors are to be minimized. The organic loading rate can be checked by the following expression:

$$L_{org} = \frac{(C)(d_w)(\eta)(F_1)}{t \times F_2} \qquad (9\text{-}8)$$

where L_{org} = organic loading rate, lb BOD/ac·d (kg BOD/ha·d)
C = BOD concentration in influent, mg/L (g/m^3)
d_w = depth of flow, ft (m)
η = plant based void ratio, 0.65 to 0.75 typically
F_1 = conversion factor, 8.34 lb/[Mgal·(mg/L)] (0.001 kg/g)
t = detention time, d
F_2 = conversion factor, 3.07 ac·ft/Mgal (10^{-4} ha/m^2)

Required surface area. Once the detention time is calculated, the net area of the wetland can be determined from

$$A = (Q_{ave})(t)(3.07)/(d_w)(\eta) \tag{9-9}$$

where Q_{ave} = average daily flow through the wetland, Mgal/d, and A = area, ac. Other terms are as described previously.

The average flow through the wetland can be estimated by the following equation:

$$Q_{ave} = \frac{Q_{in} + Q_{out}}{2} \tag{9-10}$$

The average flow must be used to account for the influence of evapotranspiration, seepage losses, and precipitation. Evapotranspiration values for wetland plants are typically equal to the potential evapotranspiration from an open water surface (Reed et al., 1995). The calculation of required area is illustrated in Example 9-4. The two design methods are compared in Example 9-5.

Water balance. In the arid west, where evapotranspiration exceeds precipitation on an annual basis, it may be necessary to conduct a water balance to determine the effect of evapotranspiration on detention time and effluent water quality. For reuse wetlands, the net loss of water is by evapotranspiration and percolation. The water balance approach is detailed in Chap. 10, Sec. 10-3, and consists of monthly tabulations of inflow, precipitation, evapotranspiration, seepage or percolation, and outflow or storage. The flowrate values are converted to inches per month (in/mo) or millimeters per month (mm/mo) to allow the outflow values to be calculated. If the evapotranspiration rate is a large portion of the inflow (greater than 25 percent), the effects on water quality, particularly trace metals such as selenium, should be evaluated.

Aspect ratio. The surface dimensions can be determined by the following expression:

$$w = \left(\frac{A}{R_A}\right)^{1/2} \tag{9-11}$$

where w = width of FWS wetland, ft (m)
A = area of FWS wetland, ft² (m²)
R_A = aspect ratio, length/width

To minimize short circuiting of wastewater from the inlet to the outlet, relatively large aspect ratios (length-to-width) of rectangular basins have been proposed. If large aspect ratios (greater than 10:1) are used, a relatively large hydraulic gradient is needed to prevent backup and overflow problems in the wetland cells. Aspect ratios of 2:1 to 4:1 have been used (Reed et al., 1995).

EXAMPLE 9-4. DETERMINE AREA REQUIRED FOR BOD REMOVAL IN A FWS CONSTRUCTED WETLAND. Determine the area required for a FWS constructed wetland used to treat

primary treated wastewater with an influent BOD of 100 mg/L. To be assured of odorless operation, the maximum organic loading rate is to be equal to or less than 100 lb BOD/ac·d. Assume the overall first-order BOD removal rate constant is 1.0 d⁻¹ at 20°C. The average wastewater temperature during the coldest month is about 10°C. The average water depth is to be 1.25 ft. Because of evaporation, the effluent flowrate is equal to 0.8 × the influent flow rate. Assume that the plant porosity is 0.70 and that the average BOD in the effluent due to plant decay is 5 mg/L. The combined effluent BOD (from plant decay and residual from influent) must be 25 mg/L or less. The observed temperature coefficient and COR values for a similar FWS system in the same temperature regime are 1.02 and 0.50 (at 99 percent), respectively. Compare the detention time to that calculated by using Eq. (9-6).

Solution

1. Determine the maximum allowable residual BOD from the influent wastewater that can be present in the effluent from the wetland using Eq. (9-4):

$$\begin{aligned} BOD_{RIW} &= BOD_{ECW} - BOD_{PD} \\ &= 25\text{ mg/L} - 5\text{ mg/L} = 20\text{ mg/L} \end{aligned}$$

2. Determine the required detention time using Eq. (9-5), for a cascade of four reactors in series, to account for axial dispersion in an ideal plug-flow reactor:

$$t = \frac{V}{Q} = \left[\frac{1}{(C_n/C_o)^{1/n}} - 1\right] \times \frac{n}{k_o}$$

   a. Determine the temperature-corrected overall BOD removal-rate constant using Eq. (3-15):

$$\begin{aligned} k_{o(10)} &= k_{o(20)} \times 1.02^{(10-20)} \\ &= 1.0/\text{d} \times 1.02^{(10-20)} = 0.82\text{ d}^{-1} \end{aligned}$$

   b. Determine the required detention time:

$$t = \left[\frac{1}{(20/100)^{0.25}} - 1\right] \times \frac{4}{0.82} = 2.4\text{ d}$$

3. Check the required detention time using the COR approach.
   a. Determine the required effluent concentration based on the COR value:

$$BOD_{DES} = BOD_{RIW} \times (COR) = 20 \times 0.50 = 10\text{ mg/L}$$

   b. Determine the detention time based on first-order BOD removal kinetics [Eq. (9-6)]:

$$\begin{aligned} t &= -\frac{\ln(C/C_o)}{k_o} \\ &= -\frac{\ln(10/100)}{1.0\text{ d}} = 2.3\text{ d} \end{aligned}$$

4. Determine the detention time using the apparent k value of 0.678 at 20°C:
   a. Calculate k using Eq. (3-15):

$$\begin{aligned} k &= 0.678 \times 1.02^{(10-20)} \\ &= 0.556\text{ d}^{-1} \end{aligned}$$

b. Determine the detention time based on $k_{apparent}$ [Eq. (9-6)]:

$$t = -\ln(C/C_o)/k$$
$$= 2.5 \text{ d}$$

Use 2.5 d detention time as the most conservative of the three approaches.

5. Check the organic loading rate using Eq. (9-8):

$$L_{org} = \frac{(C)(d_w)(\eta)(F_1)}{t \times F_2}$$
$$= \frac{(100)(1.25)(0.7)(8.34)}{2.5 \times 3.07} = 95 \text{ lb BOD/ac·d}$$

6. Determine the area required using Eq. (9-9):

$$A = (Q_{ave})(t)(3.07)/(d_w)(\eta)$$

a. Determine the value of Q_{ave}:

$$Q_{ave} = \frac{1.0 + 0.8(1)}{2} = 0.9 \text{ Mgal/d}$$

b. Determine the area:

$$A = (0.9)(2.5)(3.07)/(1.25)(0.7) = 7.9 \text{ ac}$$

Comment. The value of k_o in Eq. (9-5) is assumed, whereas the $k_{apparent}$ value of 0.678 has been derived from a number of operating systems. The use of Eq. (9-6) is recommended for design.

If the coefficient of reliability (COR) is extremely low, a larger area will be required. However, as will be shown subsequently, the area required for the removal of nitrogen will far exceed the area required for BOD and TSS removal.

EXAMPLE 9-5. COMPARISON OF DESIGN METHODS. Compare the design approach used for a FWS constructed wetland at Ouray, Colorado, to the design approach using the coefficient of retardation COR as outlined in Sec. 9-2 and in Chap. 3. The summer temperature of the water in the constructed wetland is 15.9°C. The average influent BOD is 73 mg/L. The required effluent BOD is equal to or less than 30 mg/L. The overall apparent BOD removal-rate constant used in the design was 0.678 d^{-1} at 20°C.

Solution—Existing design from Ouray, Colorado (Andrews, 1996)

1. Determine the maximum allowable residual BOD from the influent wastewater that can be present in the effluent from the wetland using Eq. (9-4):

$$BOD_{RIW} = BOD_{ECW} - BOD_{PD}$$
$$= 30 \text{ mg/L} - 4 \text{ mg/L} = 26 \text{ mg/L}$$

2. The required detention time was determined from Eq. (9-6):

$$t = -\frac{\ln C/C_o}{k_{apparent}}$$

where C = effluent BOD concentration = 26 mg/L
C_o = influent BOD concentration = 73 mg/L
$k_{apparent}$ = overall BOD removal-rate constant, corrected for temperature, d^{-1}

a. The apparent overall BOD removal rate constant is temperature-corrected by using Eq. (3-15):

$$k_{15.9} = k_{20} \times 1.06^{(15.9-20)}$$
$$= (0.678/\text{d}) \times 1.06^{-4.1} = 0.53 \text{ d}^{-1}$$

b. The required detention time was then computed as follows:

$$t = -\frac{\ln(26/73)}{0.53} = 1.95 \text{ d}$$

Solution—Design based on COR approach using actual performance data (Andrews, 1996)

3. Estimate the overall BOD removal-rate constant using Eq. (9-5) for a cascade of four reactors in series to account for axial dispersion:

$$k_o = \left[\frac{1}{(C_n/C_o)^{1/n}} - 1\right] \times \frac{n}{t}$$

a. Determine the temperature-corrected overall BOD removal-rate constant:

$$k_o = \left[\frac{1}{(26/73)^{0.25}} - 1\right] \times \frac{4}{1.95} = 0.6 \text{ d}^{-1}$$

b. Estimate the 20°C overall BOD removal-rate constant.

$$k_{o(20)} = \frac{k_{o(10)}}{1.06^{(15.9-20)}} = \frac{0.60}{0.787} = 0.76 \text{ d}^{-1}$$

4. Determine the required detention time using the COR approach.
   a. Determine the required effluent BOD design concentration. Using the actual performance data from the Ouray system, the COR value, based on meeting a specified effluent limit 90 percent of the time, was found to be equal to 0.622 (see Example 9-3).

$$BOD_{DES} = BOD_{RIW} \times (COR) = 26 \times 0.622 = 16.2 \text{ mg/L}$$

   b. Determine the detention time based on first-order BOD removal kinetics:

$$t = -\frac{\ln C/C_o}{k_o}$$
$$= -\frac{\ln(16.2/73)}{0.76/\text{d}} = 1.98 \text{ d}$$

Comment. A factor of safety of 15 to 25 percent is typically applied to the calculated detention time when Eq. (9-5) is used. In this case, the 1.95-d detention time determined in step 2 would be increased from 2.2 to 2.4 d. With the COR approach, the factor of safety is built in at the 90 percent level of reliability. For example, if the effluent reliability limit was 99 percent, the corresponding detention time would be equal to 2.4 d.

Loading rates for TSS removal. The removal of TSS is the result of physical interactions within the wetland. The removal of TSS has been related to the hydraulic loading rate, as given by the following empirical equation.

$$C_e = C_o[0.1139 + 8.4 \times 10^{-4}(L_W)] \tag{9-12}$$

where C_e = effluent TSS, mg/L
C_o = influent TSS, mg/L
L_W = wastewater hydraulic loading rate, in/d

Detention time for nitrogen removal. Longer detention times are necessary, typically, for nitrification and nitrogen removal than for BOD removal. In addition, the BOD loading rate must be relatively low so that the bacteria responsible for nitrification can obtain adequate oxygen to function.

The following first-order plug-flow equation can be used to predict ammonia nitrogen removal (Reed et al., 1995):

$$\frac{N_e}{N_o} = e^{-kt} \tag{9-13}$$

where N_e = effluent ammonia-nitrogen concentration, mg/L
N_o = influent ammonia-nitrogen concentration, mg/L
k = 0.2187 d^{-1} (at 20°C)
t = detention time, d

As noted previously in Sec. 9-2, in applying Eq. (9-13) all of the organic and ammonia nitrogen present is assumed to be in the form of ammonia. As more information is developed, it may be possible to model the various fractions of nitrogen (e.g., soluble, colloidal, and particulate).

If it is necessary to approximate the ammonia removal for conditions of temperature below 10°C, the recommended procedure would be to reduce the k value to 0.0389. For temperatures of 1°C and higher, use a θ value of 1.048 in Eq. (3-22) (Reed et al., 1995).

Nitrate removal can also be predicted from Eq. (9-13) by using a k factor of 1.0 and a θ value of 1.15. Nitrate removal is relatively rapid, provided that ample carbon is available in the system.

Total nitrogen removal can be estimated by combining the steps of ammonia transformation (nitrification) and nitrate removal (denitrification). To check the calculated total nitrogen removal, use Eq. (9-14). To obtain 50 percent removal of nitrogen, Eq. (9-14) would predict a hydraulic loading rate of 2 in/d or less (assuming the total nitrogen concentration in the influent is less than 20 mg/L) (WPCF, 1989). The empirical relationship represented by Eq. (9-14) is the result of a regression analysis with an r^2 value of 0.79.

$$N_t = 0.193N_o + 3.94(L_W) - 1.75 \tag{9-14}$$

where N_t = effluent total nitrogen concentration, mg/L
N_o = influent total nitrogen concentration, mg/L
L_W = wastewater hydraulic loading rate, in/d

The hydraulic loading rate can be used to calculate the net wetland area from

$$A = \frac{QF}{L_W} \tag{9-15}$$

where A = net wetland area, ac (ha)
Q = average flow, Mgal/d (m^3/d)
F = conversion factor, 36.8 ac·in/Mgal (0.1 ha·mm/m^3)
L_W = wastewater hydraulic loading rate, in/d (mm/d)

Hydraulic loading rates have ranged from 0.3 to 2.5 in/d (7.5 to 62.5 mm/d) for operating FWS constructed wetlands. Detention times for significant nitrogen removal (10 mg/L removal or more) should be in the range of 8 to 14 days or more. Nitrogen removal and nitrification will be reduced when water temperatures fall below 10°C and cannot be expected when water temperatures fall below 4°C.

Loading rates for phosphorus removal. A first-order (area-based) rate constant of 10 m/yr (27.4 mm/d) has been proposed for estimating phosphorus removal in constructed wetlands (Kadlec and Knight, 1996).

$$C_e/C_o = \exp(-k_A/L_{\overline{W}}) \tag{9-16}$$

where C_e = effluent phosphorus, mg/L
C_o = influent phosphorus, mg/L
k_A = 1.07 in/d (27.4 mm/d)
$L_{\overline{W}}$ = average annual wastewater hydraulic loading rate, in/d (mm/d)

To calculate the land requirement, use

$$A = -Q_{ave}\ln(C_e/C_o)F/k_A \tag{9-17}$$

where A = surface area of wetland, ft^2 (m^2)
Q_{ave} = average wastewater flowrate through the wetland, ft^3/d (m^3/d)
F = conversion factor, 12 in/ft (1000 mm/m)

Water depth. Water depth can range from 4 to 18 in (100 to 450 mm). For warm water conditions the 4 to 8 in (100 to 200 mm) range is typical. Storage of wet-weather flows can be accommodated for short periods (30 d or so) at depths of 20 to 40 in (500 to 1000 mm).

Hydraulic considerations. In FWS wetlands, the headloss from vegetation must also be considered. The hydraulic gradient can be estimated by using the following modified form of Manning's equation:

$$v = \frac{1}{n}(d_w^{2/3})(s^{1/2}) \tag{9-18}$$

where v = liquid flow velocity, ft/s (m/s)
n = Manning's coefficient, s/$ft^{1/3}$ (s/$m^{1/3}$)
d_w = depth of water in wetland, ft (m)
s = hydraulic gradient or slope of the water surface, ft/ft (m/m)

The resistance factor a depends on the density of the vegetation and litter. The factor is related to Manning's n as follows:

$$n = \frac{a}{d_w^{1/2}} \tag{9-19}$$

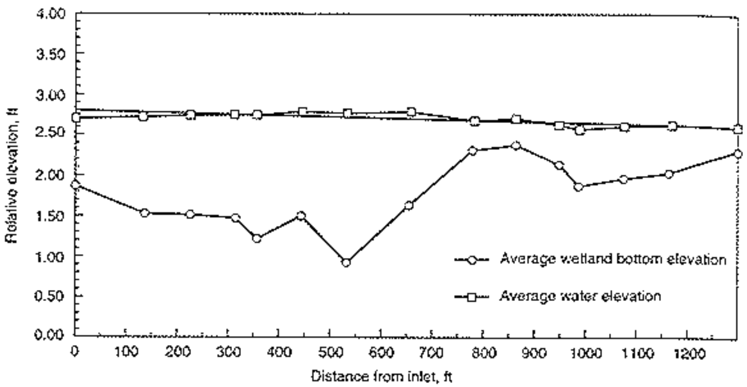


FIGURE 9-10
Hydraulic profile along centerline of FWS constructed wetland at Sacramento, California.

where a = resistance factor, s·ft$^{1/6}$ (s·m$^{1/6}$)
= 0.487 for sparse vegetation and $d_w > 1.3$ ft
= 1.949 for moderately dense vegetation in a wastewater wetland for d_w = 1.0 ft
= 7.795 for very dense vegetation and litter layer, $d_w < 1.0$ ft

The application of Eqs. (9-18) and (9-19) is illustrated in Example 9-6. A typical profile along the centerline of one of the plug-flow channels in the Sacramento Regional constructed wetland is shown in Fig. 9-10.

EXAMPLE 9-6. HYDRAULICS OF FWS CONSTRUCTED WETLANDS. A FWS wetland has an aspect ratio of 3:1 and a wastewater hydraulic loading rate of 3 in/d. For a flow of 0.5 Mgal/d and a depth of 1 ft, calculate the area, dimensions, and flow velocity. Calculate Manning's n and the hydraulic gradient. Assume the value of the resistance factor a is 1.949.

Solution

1. Determine the field area using Eq. (9-15):

$$A = \frac{QF}{Lw} = \frac{0.5(38.6\text{ ac·in/Mgal})}{3\text{ in/d}} = 6.1\text{ ac}$$

2. Calculate the width of the cell using Eq. (9-11):

$$w = (A/R_A)^{1/2} = \left[\frac{(6.1)(43,560\text{ ft}^2/\text{ac})}{3}\right]^{1/2}$$

$$W = 298\text{ ft}$$

$$L = 3W = 894\text{ ft}$$

3. Calculate the velocity:

$$v = \frac{Q}{d_w w} = \frac{(0.5\text{ Mgal/d})(3.07\text{ ac·ft/Mgal})(43,560\text{ ft}^2/\text{ac})}{(1\text{ ft})(298\text{ ft})}$$

$$= 224\text{ ft/d}$$

$$= 0.0026\text{ ft/s}$$

4. Calculate Manning's n:

$$n = \frac{a}{d_w^{1/2}} = \frac{1.949\text{ s·ft}^{1/6}}{1^{1/2}} = 1.949\text{ s·ft}^{1/3}$$

5. Calculate the hydraulic gradient:

$$v = \frac{1}{n}(d_w^{2/3})(s^{1/2})$$

$$s^{1/2} = \frac{v}{(1/n)(d_w^{2/3})} = \frac{0.0026}{(1/1.949)(1^{2/3})}$$

$$s = 0.0000257\text{ ft/ft}$$

6. Determine the headloss for a length of 894 ft:

$$h_L = sL = 0.0000257(894\text{ ft}) = 0.023\text{ ft}$$

Comment. No losses of flow through seepage or evaporation were assumed in the calculation of the velocity and the gradient. Flow losses will reduce the velocity and the resulting gradient. The headloss of 0.023 ft is acceptably small.

Thermal considerations. In very cold climates wetlands will be impacted by temperatures below 1°C (33.8°F). Constructed wetlands can operate successfully in cold climates as evidenced by the numerous systems in Canada (Pries, 1996). Where water temperatures between 1 and 4°C (34 and 40°F) are expected for more than a month, data from existing plants should be analyzed using the methods outlined in Chap. 3. For cold-climate design, the thermal models in Reed et al. (1995) should be consulted.

Vegetation harvesting. Periodic harvesting of the emergent vegetation may be required to maintain hydraulic capacity, promote active growth, or avoid mosquito production. Harvesting for nutrient removal is not practical, and is not recommended. Harvesting activity will affect performance, so the harvested cell should be taken out of service before and for several weeks after harvesting. Harvested vegetation can be burned, chopped and composted, or chopped and used as mulch.

Vegetation planting and establishment. An important aspect of design is the preparation of a strong specification for vegetation planting and establishment. Planting can be done by seeding or transplanting most species. Contractors are generally not expert in planting wetland vegetation and initial plantings may fail.

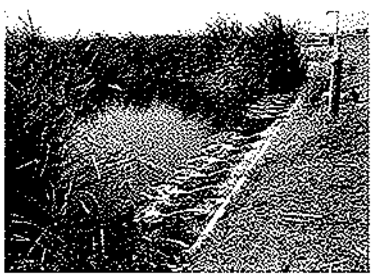
Experience has shown that 0.5 to 2 years may be required before vegetation in a constructed wetland becomes established fully.

Physical Features of FWS Wetlands

The principal physical features of FWS constructed wetlands include inlet and outlet structures, recirculation, and liners.

Inlet and outlet structures. Uniform distribution of wastewater across the head end of the FWS wetland is critical to a successful system (see Fig. 9-11). Gated pipe, weirs, or drilled holes in distribution pipelines can be used to spread the wastewater across the inlet end of the wetland. Features of outlet structures include adjustable weirs with stop logs and submerged outlet header pipes with control valves. The ability to vary the water depth and to drain the basin should be provided. Basins should be sloped at 0.4 to 0.5 percent grade to facilitate draining.

Recirculation. The ability to recirculate partially or fully treated effluent back to the head end of the basin is an important consideration. Recirculation can reduce organic and solids concentrations, provide more dissolved oxygen to the inlet point,



(a)

(b)

FIGURE 9-11
Typical (*a*) inlet and (*b*) outlet devices at the Sacramento Regional CSD free-water-surface (FWS) constructed wetland.

and improve overall performance. Recirculation is most effective when combined with step feed (see Sec. 9-5).

Liners. A constructed wetland may need a liner to seal the bottom and sides and thereby prevent or minimize seepage. Depending on the site selected, soil type, groundwater depth and quality, level of pretreatment, and regulatory considerations, a natural or synthetic liner may be required. Bentonite clay is a typical earthen liner while geomembrane liners are also available (Kays, 1986).

9-4 SUBSURFACE-FLOW CONSTRUCTED WETLANDS

A constructed wetland with the flow beneath the surface of a gravel or sand medium is known as a subsurface-flow (SF) system. The process description, constituent removal and transformation mechanisms, performance expectations, and process design considerations are presented and discussed in this section. General design considerations and the management for these systems are discussed in Secs. 9-8 and 9-9, respectively.

Process Description

Subsurface-flow systems have also been termed *rock-reed filters, microbial rock plant filters, vegetated submerged beds, marsh beds, tule beds,* and *hydrobotanical systems.* In Germany a similar type of system that uses native soil and reeds is known as the *root zone method.* Subsurface-flow systems have the advantages of smaller land area requirements and avoidance of odor and mosquito problems, as compared to free-water-surface (FWS) systems. Disadvantages of SF systems are the increased cost due to the gravel media and the potential for clogging of the media. Pretreatment for SF wetlands typically consists of primary treatment.

Site selection. The SF wetland takes less space than a comparable FWS system and generally has a sloped bottom of 0 to 0.5 to percent. If soils are permeable (greater than 0.2 in/h) it may be necessary to install a liner below the bed medium.

Vegetation types. The vegetation in SF systems is similar to FWS wetlands and tends to be bulrush, reeds, and in some cases cattails. The purpose of the vegetation is to provide oxygen into the root zone and add to the surface area for biological growth in the root zone. The actual transport of oxygen to the root zone and then into the water column is limited (Brix, 1993). The roots also release organics as they decay, which supports denitrification. The aboveground portion of the vegetation provides little benefit except for nutrient uptake and plant growth. Plant harvesting is not necessary (Gersberg et al., 1985).

Bed medium. The subsurface flow wetland medium is usually gravel, although in early systems sand was also used. The gravel size has varied from 0.12 in

TABLE 9-10
Typical medium characteristics for SF wetlands

Medium type	Effective size d_{10}, mm	Effluent porosity η	Hydraulic conductivity, ft/d
Medium sand	1	0.30	1640
Coarse sand	2	0.32	3280
Gravelly sand	8	0.35	16,400
Medium gravel	32	0.40	32,800
Coarse gravel	128	0.45	328,000

Note: d_{10} is the diameter of a particle in a weight distribution of particles that is smaller than all but 10% of the particles.

to 1.25 in (3 to 32 mm), with inlet zone gravel size as large as 2 in (50 mm). The inlet zone should have the largest-diameter medium to minimize the clogging potential. At Sydney, Australia, the medium in the inlet zone is 1.2 in to 1.6 in (30 to 40 mm) in diameter while in the remainder of the bed the medium is 0.2 in to 0.4 in (5 to 10 mm). Characteristics of SF media are presented in Table 9-10.

Constituent Removal and Transformation Mechanisms

As with FWS wetlands, SF wetlands can be expected to produce a high-quality effluent in terms of BOD, TSS, and pathogens. The principal removal mechanisms are biological conversion, physical filtration and sedimentation, and chemical precipitation and adsorption as described in the FWS wetlands section. Lesser removal of nitrogen, phosphorus, metals, and trace organics than for BOD and TSS should be expected, with removals dependent on detention time, media characteristics, loading rates, and management practices.

BOD removal. Removal of BOD is accomplished biologically and physically. Removal of BOD occurs primarily under anaerobic conditions; however, a portion of the BOD is converted by facultative organisms. The rate of removal is related to detention time and temperature as described under "Process Design Considerations."

Suspended solids removal. The mechanisms for TSS removal are similar to those for TSS removal from FWS systems. The lack of a free water surface in SF wetlands avoids the wind currents and resuspension of solids, resulting in the potential for a lower effluent TSS concentration. The majority of the solids settle out or are trapped within the first 10 to 20 percent of the bed flow distance. Observations at a number of operating SF systems indicated clogging of the inlet zone resulting in surface flow down a portion of the flow path. The clogging appears to be the result of the high solids and organic loading occurring at the entry zone of the bed. The most severe clogging has occurred with long narrow beds receiving algae-laden effluent from facultative ponds. The algae are trapped in the medium near the inlet and the decomposing algae add to the organic load.

Nitrogen removal. Nitrogen removal is accomplished by nitrification/denitrification. Although SF wetlands have the ability to denitrify the available nitrate-nitrogen, the limitation on nitrogen removal is the nitrification step. The subsurface flow regime is nearly anaerobic, except for the top few inches and aerobic microsites near the plant roots. Nitrification requires a supply of oxygen, either from the plant roots, surface reaeration, effluent recirculation, or batch loading to induce oxygen flow down into the media between applications. Supplemental aeration using subsurface tubing can be used to provide oxygen at a point in the flow path where the BOD has been reduced below 30 mg/L, so that the oxygen provided is of use to the nitrifying bacteria.

Phosphorus removal. The mechanisms for phosphorus removal are essentially the same as for FWS wetlands. Special media are required to effect substantial removal of phosphorus by adsorption. As in the FWS systems, phosphorus can be released during certain times of the year, usually in response to changes in the environmental conditions within the system.

Metals removal. The removal mechanisms for metals include adsorption, sedimentation, chemical precipitation, and plant uptake. As in the FWS systems, metals can be released during certain times of the year, usually in response to change in the oxidation-reduction potential (ORP) within the system.

Trace organics removal. Removal mechanisms for trace organics are similar to those for FWS wetlands except that volatilization and photodecomposition are limited.

Pathogen removal. Removal of bacteria and viruses occurs by adsorption, filtration, sedimentation, and predation.

Process Performance

The performance expectations for SF constructed wetlands are considered in the following discussion. As with the FWS system, process performance depends on design criteria, wastewater characteristics, and operations.

BOD removal. Performance data for BOD removal are presented in Table 9-11. Removal of BOD appears to be faster and somewhat more reliable with SF wetlands than for FWS wetlands, partly because the decaying plants are not in the water column, thereby producing slightly less organic matter in the final effluent.

TSS removal. SF wetlands are efficient in removal of suspended solids, with effluent TSS levels below 10 mg/L, typically.

Nitrogen removal. Although the SF system at Santee was able to remove 86 percent of the nitrogen from primary effluent, other SF systems have reported

TABLE 9-11
Total BOD removal observed in SF wetlands

Location	Pretreatment	Concentration, mg/L		Removal, %	Nominal detention time, d
		Influent	Effluent		
Benton, Kentucky*	Oxidation pond	23	8	65	5
Mesquite, Nevada†	Oxidation pond	78	25	68	3.3
Santee, California‡	Primary	118	1.7	88	6
Sydney, Australia§	Secondary	33	4.6	86	7

*Full-scale operation from March 1988 to November 1988 at 80 mm/d (Watson et al., 1989).
†Full-scale operation, January 1994 to January 1995.
‡Pilot-scale operation, 1984, operated at 50 mm/d (Gersberg et al., 1985).
§Pilot-scale operation at Richmond, New South Wales, near Sydney, operated at 40 mm/d from December 1985 to February 1986 (Bavor et al., 1987).

removals of from 20 to 70 percent. When detention times exceed 6 to 7 d, an effluent total nitrogen concentration of about 10 mg/L can be expected, assuming a 20 to 25 mg/L influent nitrogen concentration. If the applied wastewater has been nitrified (using extended aeration, overland flow, or recirculating sand filters), the removal of nitrate through denitrification can be accomplished with detention times of 2 to 4 d.

Phosphorus removal. Phosphorus removal in SF wetlands is largely ineffective because of limited contact between adsorption sites and the applied wastewater. Depending on the loading rate, detention time, and media characteristics, removals may range from 10 to 40 percent for input phosphorus in the range from 7 to 10 mg/L. Crop uptake is generally less than 10 percent (about 0.5 lb/ac·d)(0.55 kg/ha·d).

Metals removal. There are limited data available on metals removal using municipal wastewater in SF systems. In acid mine drainage systems, removal of iron and manganese is significant. Total iron has been shown to be reduced from 14.3 to 0.8 mg/L and total manganese from 4.8 to 1.1 mg/L (Brodie et al., 1989). At Santee, California, removal of copper, zinc, and cadmium was 99 percent, 97 percent, and 99 percent, respectively, during a 5.5-d detention time (Gersberg et al., 1984).

Pathogen removal. A removal of 99 percent (2 log) of total coliform was found when primary effluent was applied at 2 in/d (detention time 6 d) at Santee, California (Gersberg et al., 1989).

Process Design Considerations

Important process design criteria include detention time, required surface area, BOD and solids loading rates, and medium depth. Representative process design criteria are presented in Table 9-12. The design procedure is illustrated in Example 9-7.

TABLE 9-12
Typical design criteria and expected effluent quality for SF constructed wetlands

Item	Unit	Value
Design parameter		
Detention time	d	3–4 (BOD) 6–10 (N)
BOD loading rate	lb/ac·d	<100
TSS entry loading rate	lb/ft²·d	0.008
Water depth	ft	1–2
Medium depth	ft	1.5–2.5
Mosquito control		Not needed
Harvest schedule		Not needed
Expected effluent quality*		
BOD_5	mg/L	<20
TSS	mg/L	<20
TN	mg/L	<10
TP	mg/L	<5

*Expected effluent quality based on a BOD loading equal to or less than 100 lb/ac·d and typical municipal wastewater.

Detention time for BOD removal. The detention time is determined by using Eq. (9-6). The value of the apparent removal rate constant at 20°C is about 1.1 d^{-1}. The overall BOD loading on SF wetlands should not exceed about 100 lb/ac·d (112 kg/ha·d). These rates will not be exceeded in practice with primary effluent applied at up to 2 in/d (50 mm/d).

Like FWS wetlands, SF wetlands experience some regeneration of BOD due to decay, primarily from the roots because the decaying vegetation stays on the surface on the bed and remains out of the water column. Depending on the time of year, there will be some accretion from the surface vegetation. The root decay will generate 2 to 3 mg/L of BOD_{PD}.

Required surface area. Once the detention time is calculated the net area of the wetland can be determined from

$$A_s = \frac{(Q_{ave})(t)(3.07)}{(\eta)(d_w)} \tag{9-20}$$

where Q_{ave} = average daily flow through the wetland, Mgal/d, and A_s = surface area, ac. Other terms are as described previously. The average flow through the wetland can be estimated from Eq. (9-10).

Aspect ratio. The surface dimensions of the SF wetland can be determined by using Eq. (9-11) as given previously in the discussion of FWS systems. Aspect ratios should be determined in conjunction with Darcy's law (Eq. 9-23).

Suspended solids entry zone loadings. If an aspect ratio greater than about 4:1 is used, the influent solids loading may be of concern. To avoid clogging

TABLE 9-13
Comparison of the behavior of sand, gravel, and rock filters operated at various suspended solids loading rates*

Material	Typical particle size, mm	Nominal TSS loading rate, g/m²·d	Performance
Sand	0.17	5	Clogging in > 5 years
		10	Clogging in 50 days
		30	Clogging in < 10 days
	0.40	10	Clogging in > 0.5 years
		30	Clogging in 35 days
		70	Clogging in 10 days
	0.68	20	Clogging in > 0.5 years
		40	Clogging in 50 days
		80	Clogging in 20 days
Gravel	5–10 (inlet)	40	Infiltration for 3+ years
	5–10 (w/g)	200	Clogging in 3 months
	40 (inlet)	18	Infiltration for 3+ years
	40 (inlet-primary)	80–160	Infiltration for 1+ year
Rock	9–25	13–464†	Clogging in 11 months
	10–50	113–629†	Infiltration for 17+ months, but poor TSS removal
	63–127	102‡	Infiltration for 14+ months, but poor TSS removal

*From Bavor and Schulz (1993).
†Represents loadings with 50 mg/L algal solids.
‡Represents loadings with 69 mg/L algal solids.
Notes: The loading rates were those estimated to apply per square meter of surface available for infiltration. The data for sand and rock filters are adapted from Middlebrooks et al. (1982). Gravel filters were at Eudora, Kansas, and California, Missouri. Surface areas were estimated from the volumetric loading rates and estimates of the open surface in the illustrated designs. Gravel size at the water/gravel interface is noted as w/g.

of the inlet zone with suspended solids, the entry-zone solids loading values must be checked. Although suspended solids loading limits have not been developed in this country, experience in Australia has led to the recommendation that entry-zone TSS limits not exceed 0.008 lb/ft²·d (Bavor et al., 1989), where the area used in the loading rate is the cross-sectional area of the entry zone. Soil clogging experience as a function of medium size is compared in Table 9-13.

The entry zone organic loading rate can be computed as follows:

$$L_{TSS} = \frac{\text{constituent mass loading, lb/d}}{\text{entry zone cross-sectional area, } w\, d_m,\ \text{ft}^2} \tag{9-21}$$

where w = width of SF wetland, ft, and d_m = depth of medium, ft.

Depth of medium. The depth of the medium may range from 18 to 30 in (450 to 750 mm). Typical rooting depths range from 6 to 12 in. To obtain rooting depths of 12 in or more, the water depth must be systematically lowered over a number of growing seasons to force the roots to penetrate deeper. The depth of the medium does not have to be much deeper than the rooting depth. The water level is kept 3 to 6 in (75 to 150 mm) below the top of the medium.

Detention time for nitrogen removal. Some SF systems have been designed for ammonia removal, with the previously mentioned problem of inadequate oxygen availability. On the basis of pilot studies in Australia, the following relationship between detention time and ammonia removal was developed (Bavor et al., 1987):

$$A = \frac{Q(\ln N_o - \ln N_e)}{k(d_w)(\eta)(F)} \tag{9-22}$$

where A = surface area of SF wetland for NH_4-N removal, ac (ha)
Q = average flow through the wetland, ft³/d (m³/d)
N_o = influent NH_4-N concentration, mg/L
N_e = effluent NH_4-N concentration, mg/L
k = 0.107 d^{-1} (for 20°C)
d_w = depth of liquid in bed, ft (m)
η = effective porosity of bed medium expressed as a decimal
F = conversion factor, 43,560 ft²/ac (10,000 m²/ha)

The temperature dependence of k can be calculated using Eq. (3-22) and a θ value of 1.15.

Hydraulic considerations. Headloss through SF wetlands can be estimated from Darcy's law:

$$A = d_w w = \frac{Q}{kS} \tag{9-23}$$

where A = cross-sectional area of inlet zone, perpendicular to the flow path, ft (m)
d_w = depth of liquid in bed, ft (m)
w = bed width, ft (m)
Q = flow into system, ft³/d (m³/d)
k = hydraulic conductivity from Table 9-10 (or measured in field, preferably), ft/d (m/d)
S = slope, expressed as a decimal (headloss)

In using Eq. (9-23), the measured value of k should be used when available and multiplied by a safety factor of 10 percent to account for root and tuber growth. In the absence of measured data, use the values in Table 9-10 multiplied by 10 percent. For sloped beds, use the bottom slope, which can vary from 0 to 1 percent or more. When a flat bed is used and the gradient is controlled with an overflow weir, use 0.001 for S.

Vegetation establishment. For very small systems [less than 2 ac (0.8 ha)] vegetation can often be transplanted from nearby sources or obtained commercially. Rhizome cuttings should be 4 in (100 mm) long and have a growing shoot at the end of the cutting. The root end of the cutting should be placed about 2 in (50 mm) below the media surface. The bed should then be flooded with water to the surface or sprinkled frequently. If flooding is used, the water level must be maintained carefully during this period so that the exposed plant shoots are not submerged.

Planting densities for the most commonly used species are 3-ft (1-m) centers for cattails, 1.5-ft (0.5-m) centers for reeds and bulrush (Reed et al., 1995). For beds larger than 2 ac (0.8 ha) it may be more economical to hydroseed the vegetation. In any case, the vegetation should be allowed to become established with 3 to 6 months of growth before wastewater applications begin.

Physical Features of SF Wetlands

Important physical features of SF wetlands include inlet and outlet structures, recirculation, and bed liners. To provide for operational flexibility, each system should have multiple cells (minimum of 2).

Inlet and outlet structures. The inlet system must be designed so that the influent flow is distributed uniformly over the length of the entry zone. Typical devices for influent distribution are gated pipe, slotted pipe, or troughs with V-notch weirs. The first 10 ft (3 m) of the entry zone is usually filled with large rock (2 to 4 in or 50 to 100 mm) to minimize clogging. If a step feed operation is desired, a second influent distributor can be placed parallel to the entry zone distributor at a distance (50 ft or 15 m or more) down the flow path.

Outlet devices should consist of perforated pipes submerged to the bottom of the bed with valves or adjustable-level outlet pipes to control the water depth. An example outlet device is shown schematically in Fig. 9-12.

Recirculation. The ability to recirculate treated effluent to dilute influent concentrations, improve treatment, and avoid overloading can be built into SF

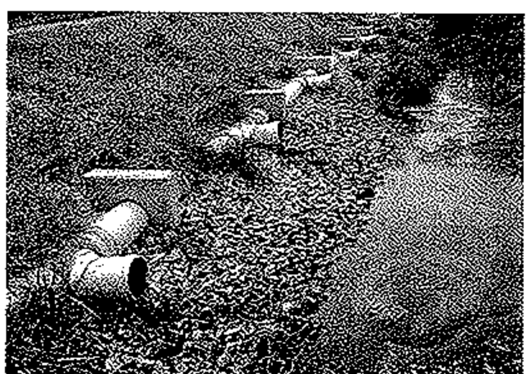


FIGURE 9-12
Typical inlet device for subsurface-flow (SF) constructed wetland at Hardin, Kentucky.

systems by using recirculation pumps and piping. If the SF effluent must be pumped to its final reuse/discharge point, recirculation pumping is very inexpensive and is recommended.

Bed liners. If the soil is permeable, a bed liner will usually be required to prevent loss of water to the groundwater. The liner may consist of native clay, bentonite, asphalt, or geomembrane liners (Kays, 1986). A smooth-surfaced 30-mil plastic membrane liner is used typically (Reed et al., 1995).

EXAMPLE 9-7. DESIGN OF SF CONSTRUCTED WETLAND. A community of 2000 generates a flow of 0.16 Mgal/d of septic tank effluent. Septic tank effluent characteristics are 130 mg/L of BOD and 20 mg/L ammonia nitrogen. Design a SF wetland to produce an effluent BOD of 10 mg/L. Determine the detention time needed to reduce the ammonia concentration to 6 mg/L. Use a 9°C temperature for the septic tank effluent during the coldest month. Use k values of 1.1 d^{-1} and 0.107 d^{-1} for BOD removal and nitrification, respectively.

Solution

1. Calculate the k_T value using Eq. (3-22) for a temperature 9°C:

$$\frac{k_T}{k_{20}} = 1.06^{(T-20)}$$

$$k_T = 1.1(1.06^{(9-20)}) = 0.58\ d^{-1}$$

2. Calculate the detention time for BOD removal using Eq. (9-6):

$$t = -\frac{\ln(C/C_o)}{k_{\text{apparent}}}$$

$$= \frac{\ln(10/130)}{0.58} = 4.42\ d$$

3. Check the organic loading rate using Eq. (9-8):

$$L_{org} = \frac{(C)(d_w)(\eta)(F_1)}{t \times F_2}$$

$$= \frac{(130)(1.25)(0.4)(8.34)}{4.42 \times 3.07} = 40\ \text{lb BOD/ac}\cdot\text{d}$$

4. Select the depth of the medium, d_w. From Table 9-12 select 1.5 ft as the medium depth.

5. Determine the field area for the SF bed using Eq. (9-20) with an effective porosity of 0.40 (see Table 9-10), a medium depth of 1.5 ft, and a liquid depth of 1.25 ft:

$$A_s = \frac{(Q_{ave})(t)(3.07)}{(\eta)(d_w)}$$

$$= \frac{(0.16)(4.42)(3.07)}{(0.40)(1.25)} = 4.34\ \text{ac}$$

6. Calculate the k value for nitrification using Eq. (3-22).

$$k_T = 0.107(1.06^{(9-20)})$$

$$= 0.056\ d^{-1}$$

7. Calculate the surface area for nitrification using Eq. (9-22):

$$A = \frac{Q(\ln N_o - \ln N_e)}{k(d_w)(\eta)(F)}$$

$$Q = (0.16 \text{ Mgal/d})(133{,}690 \text{ ft}^3/\text{Mgal})$$
$$= 21{,}390 \text{ ft}^3/\text{d}$$

$$A = \frac{21{,}390[\ln(20) - \ln(6)]}{0.056(1.25)(0.4)(43{,}560)}$$
$$= 21.0 \text{ ac}$$

8. Calculate the detention time corresponding to the 21.0 ac.

$$t = \frac{Ad_w\eta}{Q}$$
$$= (21.0 \text{ ac})(1.25 \text{ ft})(0.40)/(0.16 \text{ Mgal/d})(3.07 \text{ ac}\cdot\text{ft/Mgal})$$
$$= 21.4 \text{ d}$$

Note: This detention time is excessively long. Supplemental aeration, an RSF, and other supplemental treatment will be necessary to make this SF system cost-effective under these conditions.

9. Calculate the cross-sectional area from Darcy's law [Eq. (9-23)] using $k = 32{,}800$ from Table 9-10 multiplied by 10 percent. Use $S = 0.01$.

$$A = \frac{Q}{kS}$$
$$= \frac{(0.16 \text{ Mgal/d})(133{,}690 \text{ ft}^3/\text{Mgal})}{(32{,}800)(0.10)(0.01)}$$
$$= 652 \text{ ft}^2$$

10. Calculate the dimensions of the system.
   a. Calculate the width:

$$w = A/d$$
$$= 652 \text{ ft}^2/1.25 \text{ ft}$$
$$= 521.6 \text{ ft}$$

   b. Calculate the length:

$$L = \text{bed area/width}$$
$$= (21.0 \text{ ac})(43{,}560 \text{ ft}^2/\text{ac})/521.6 \text{ ft}$$
$$= 1754 \text{ ft}$$

   c. Calculate the aspect ratio:

$$R = L/w$$
$$= 1754/521.6$$
$$= 3.36$$

Comment. If COR data are available, the method used for the FWS can be employed. The background BOD of 3 mg/L, however, is close to the design value of 10 mg/L.

9-5 FLOATING AQUATIC PLANT SYSTEMS—WATER HYACINTHS

The two most commonly used floating aquatic plants are water hyacinths and duckweed. The use of water hyacinths is considered here. Duckweed systems are considered in the following section. The material presented in this section deals with a description of the process, constituent removal and transformation mechanisms, performance expectations, and process design considerations. General design considerations and the management for these systems are discussed in Secs. 9-8 and 9-9, respectively.

Process Description

The two principal types of water hyacinth wastewater treatment systems can be described as: (1) aerobic nonaerated and (2) aerobic aerated. *Nonaerated* aerobic systems are typically shallow arbitrary-flow ponds or plug-flow ponds (channels) covered with water hyacinths, operated without and with effluent recycle and step feed (see Figs. 9-13*a* through *f*). *Aerated* aerobic systems are similar to nonaerated

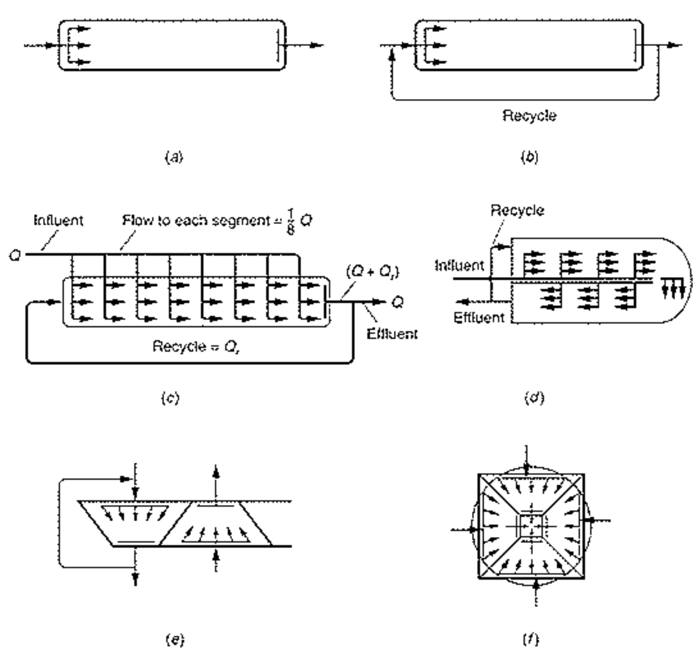


FIGURE 9-13
Alternative configurations for water hyacinth treatment basins.

plug-flow systems, with the exception that supplemental air is provided, and the operating water depths are usually greater (see Figs. 9-13*b* through *e*). An important advantage of an *aerated* system is that higher organic loading rates are possible, and reduced land area is required. *Facultative/anaerobic* ponds, of various flow configurations, employing water hyacinths have also been used. Because such systems are operated at very high organic loading rates, odors and increased mosquito populations are common. As a result of odor and mosquito problems, facultative/anaerobic water hyacinth systems are seldom, if ever, used in the United States.

Site selection. Level to slightly sloping, uniform topography is preferred for the construction of water hyacinth treatment systems. Although ponds and channels may be constructed on steeper sloping or uneven sites, the amount of earthwork required will affect the cost of the system.

Climate. Because of their sensitivity to cold temperatures, the use of water hyacinths is restricted to the southern portions of California, Arizona, Texas, Mississippi, Louisiana, Alabama, and Georgia, and all of Florida. Water temperatures as low as 10°C (50°F) can be tolerated if the air temperature does not drop below 5 to 10°C (41 to 50°F). Combined systems of several aquatic plants (e.g., duckweed, pennywort, and water hyacinth) may be suitable for locations with greater climatic variations (DeBusk and Reddy, 1987).

Water hyacinths. The water hyacinth (*Eichhornia crassipes*) is a perennial, freshwater aquatic macrophyte. The plant grows rapidly, especially in wastewater. Individual plants range from 20 to 47 in (500 to 1175 mm) from the top of the lavender flowers to the root tips. It has been estimated that starting with 10 individual plants, water hyacinths can spread and cover a 1-ac pond within 8 months (Reed et al., 1995). Water hyacinths cannot tolerate cold weather. Under freezing conditions leaves and flowers die, but the plant can regenerate unless the rhizome tip freezes. Water hyacinths die at about −6°C and cannot persist where winter temperatures average 1°C or less.

Constituent Removal and Transformation Mechanisms

High removals of BOD and TSS can be expected from properly designed water hyacinth treatment systems, with lesser efficiencies demonstrated for nutrients, metals, and pathogens. The operative removal mechanisms are described below.

Biochemical oxygen demand removal. A portion of the BOD in the influent wastewater is removed along with the TSS by sedimentation from the water column, as the wastewater flows through the treatment reactor. Another portion of the BOD associated with the suspended solids that will not settle by gravity is removed by filtration along with the TSS as wastewater flows through the roots of the water hyacinths. Soluble BOD is removed by adsorption as the wastewater flows past the water hyacinth roots. As with the removal of TSS, transport of the wastewater to the root zone is a critical design consideration with respect to the removal of soluble BOD in water hyacinth treatment systems. Soluble BOD is also removed by bacterial conversion in the water column. In time, a portion of the BOD associated with the organic fraction of the TSS accumulated in the root zone and the adsorbed soluble BOD will be converted by the organisms attached to the roots, using oxygen transported to the roots by the plant. As noted above, the roots of the water hyacinth plant will senesce and drop to the bottom of the pond or channel, carrying with them the accumulated suspended solids and bacteria. The material that accumulates on the bottom of the reactor undergoes long-term anaerobic decomposition and consolidation. There is also some release of organic material in the form of intermediate- and short-chain organic acids resulting from the first-stage anaerobic decomposition of the solids accumulated on the pond bottom. The removal of the soluble BOD represented by these acids is as described above.

Total suspended solids removal. A portion of the TSS in the influent wastewater is removed by sedimentation from the water column, as the wastewater flows through the treatment pond or channels. Another portion of the suspended solids that will not settle by gravity is removed by filtration as wastewater flows through the roots of the water hyacinths. Because filtration is such an important removal mechanism, transport of the wastewater to the root zone is a critical design consideration in water hyacinth treatment systems. In time, a portion of the organic fraction of the TSS accumulated in the root zone will be converted by the organisms attached to the roots. With the further passage of time, the TSS on the roots will continue to accumulate. Ultimately, the roots of the water hyacinth plant will senesce and drop to the bottom of the pond or channel, carrying with them the accumulated suspended solids. Additional filtration occurs as the roots drop to the bottom of the pond. The material that accumulates on the bottom of the reactor undergoes long-term anaerobic decomposition and consolidation.

Nitrogen removal. Biological nitrification-denitrification is the principal mechanism involved in the removal of nitrogen. A portion of the organic nitrogen is removed by sedimentation. Nitrogen is also taken up by plant growth and can be removed by plant harvesting, but not effectively. Some nitrogen is also lost by volatilization, where aeration is provided. The principal location where nitrification-denitrification occurs is in the root zone. Thus, it is very important for the wastewater, containing various forms of nitrogen, to flow past the water hyacinth roots where the bacteria responsible for the conversion of nitrogen are located.

Phosphorus removal. Adsorption to wastewater solids and plant material, adsorption to organic matter in sludge layer, and plant uptake are the principal means by which phosphorus is removed from wastewater. Limited amounts of phosphorus are removed where routine harvesting of water hyacinth plants is practiced. Adsorption to the organic matter in the sludge layer is the ultimate fate of the phosphorus which remains in the system. Where there are effluent limitations on phosphorus, phosphorus should be removed in a preapplication or posttreatment step, because phosphorus removal in water hyacinth treatment systems is limited, and often erratic.

Heavy metals removal. The removal of heavy metals occurs primarily through adsorption to wastewater solids and plant material. Limited plant uptake has been observed. Relatively small amounts of heavy metals are removed where water hyacinth plants are harvested. Adsorption to the organic matter in the sludge layer is the ultimate fate of heavy metals which remain in the system. As with the FWS and SF wetlands, metals can be released from the sediments, usually in response to changes in the oxidation-reduction potential (ORP) within the system.

Trace organics removal. Adsorption to wastewater solids and plant material, limited plant uptake, and biological conversion in the root zone are the principal removal mechanisms for the priority organic pollutants. As with the heavy metals, priority organic pollutants are removed where water hyacinth plants are harvested. Adsorption to the organic matter in the sludge layer is the ultimate fate of priority organic pollutants which remain in the system.

Pathogens removal. The removal of pathogens occurs by sedimentation and filtration, as described above, and natural decay within the water column. Of the operative removal mechanisms, natural decay appears to be the most effective. In systems with short hydraulic detention times, increased organism counts have been observed.

Process Performance

Typical performance data for a floating aquatic plant system using water hyacinths are presented in Tables 9-14 through 9-17. Long-term and monthly performance

TABLE 9-14
Overall constituent removal performance summary for water hyacinth wastewater treatment cells at San Diego (Aqua III), October 1994 through September 1995*

Constituent	Unit	Value		Reduction,
		Influent	Effluent	%
BOD	mg/L	148	12.6†	91
TSS	mg/L	131	9.7	93
TOC	mg/L	72	14	81
Turbidity	NTU	88	13.5	84
TS	mg/L	1322	1183	11
NH_4-N	mg/L	21	9.5	55
NO_3-N	mg/L	0.05	1.4	
TKN	mg/L	31	13.9	46
TN	mg/L	31	15.3	51
PO_4	mg/L	5.1	3.4	33
SO_4	mg/L	283	309	−9

*From WCPH (1996).
†CBOD value measured in effluent.

TABLE 9-15
Monthly BOD loading and performance summary for Aqua III water hyacinth ponds, October 1994 through September 1995

Month	Flow, Mgal/d	BOD loading, lb/ac·d	BOD, mg/L		TSS, mg/L		Turbidity, NTU	
			Influent	Effluent	Influent	Effluent	Influent	Effluent
October 1994	0.86	164	159	8.4	140	6.5	68.2	6.1
November	1.00	203	171	10.2	140	4.2	72.7	7.5
December	0.93	187	164	17.9	141	5.9	80.6	17.7
January 1995	0.86	134	125	10.3	116	10.3	83.0	13.3
February	1.05	183	140	13.2	131	10.9	93.2	14.6
March	1.02	148	119	9.3	113	8.1	82.5	10.4
April	1.16	214	152	8.6	134	6.9	95.8	12.2
May	1.22	217	147	12.0	137	8.2	95.6	13.4
June	1.16	227	142	13.7	148	9.1	95.2	13.3
July	1.14	235	144	13.8	135	14.0	93.3	15.2
August	1.16	256	149	16.3	119	14.0	91.6	16.9
September	1.19	289	158	17.0	120	18.2	95.1	20.8
Average	1.06	205	148	12.6	131	9.7	87.2	13.5

TABLE 9-16
Overall metals removal performance summary for water hyacinth wastewater treatment cells at San Diego (Aqua III), October 1994 through September 1995

Constituent	Unit	Influent	Effluent	Percent reduced
Arsenic	μg/L	2.5	1.5	40
Cadmium	μg/L	1.2	0.1	92
Chromium	μg/L	2.0	1.3	35
Copper	μg/L	42.5	9.3	78
Lead	μg/L	8.0	0.6	93
Mercury	μg/L	0.1	0.1	0
Nickel	μg/L	4.4	3.7	16
Selenium	μg/L	2.1	2.2	0
Zinc	μg/L	24.0	2.4	90

data for BOD and TSS are considered in the following discussion for the San Diego system.

Long-term performance data. Long-term performance data for the principal constituents of concern in wastewater, for the period from October 1994 through September 1995, are summarized in Table 9-14. The average pond organic loading rate during the period was 205 lb BOD/ac·d (230 kg/ha·d). As shown in Table 9-14, the effluent quality from the ponds is impressive with respect to the removal of BOD, TSS, TOC, and turbidity. As expected, significant removals of nitrogen and phosphorus were not achieved. Although not reported here, the performance data for Aqua II, the previous water hyacinth system located in Mission Valley, were essentially the

TABLE 9-17
Water hyacinth productivity data for Aqua III in San Diego, August 1994 through September 1995[*]

Month	Temperature, °F		Solar radiation, watts/m²	Amount harvested[†]		Productivity[‡]	
	Air	Water		Yd³	Wet weight, lb	Wet lb/ac·d	Dry ton/ac·yr
August 1994	77	74	450	3661	922,572	4261	51
September	72	68	430	2745	691,740	3302	39
October	63	64	360	1590	400,680	1851	22
November	51	55	340	960	241,920	1155	14
December	51	53	300	594	149,688	691	8
January 1995	54	55	340	0	0	0	0
February	61	58	380	200	50,400	258	3
March	58	62	430	950	239,400	1106	13
April	59	63	520	1150	289,800	1383	16
May	62	65	550	2134	537,768	2484	29
June	67	68	530	5638	1,420,776	6781	80
July	74	72	490	4060	1,023,120	4726	56
August	76	74	470	3324	837,648	3869	46
September	74	71	450	2399	604,548	2885	34

*From WCPH (1996).
† Total wet weight based on an average specific weight of 252 lb/yd³. Specific weight is based on average of weights measured in a 1-yd³ box.
‡ Productivity calculated as total weight harvested divided by 6.98 ac of pond surface area and total days in a month. The solids content of water hyacinths is 6.5%

same, with the exception that the concentration of the influent BOD was a bit higher (WCPH, 1996).

Monthly performance data for BOD, TSS and turbidity. Monthly performance data for BOD and TSS, for the period from October 1994 through September 1995, are summarized in Table 9-15, and illustrated graphically in Fig. 9-14. Monthly pond organic loading rates are also given in Table 9-14. The most striking thing about the data shown in Fig. 9-14 is the relatively small monthly variation in the effluent values. Properly designed and operated water hyacinth treatment systems have proven to be extremely stable (robust). When the performance and stability of the water hyacinth system at Aqua III, as shown in Fig. 9-14, are compared to comparably sized activated-sludge systems, the water hyacinth treatment system exhibits significantly more consistent effluent values as evidenced by the slope of the probability curve and the performance or stability coefficient defined as the ratio of the P_{80} to P_{10} values. The markedly steeper slopes observed with activated-sludge systems are indicative of a less stable system. Reasons for the greater stability of the water hyacinth system are, most probably, related to physiological and structural diversity provided to the treatment volume by the plant roots.

Metals removal. Typical data on the removal of metals in the water hyacinth ponds at Aqua III in San Diego are reported in Table 9-16. The limited removals achieved with nickel and arsenic are consistent with the data reported in Table 9-7 for Sacramento County.

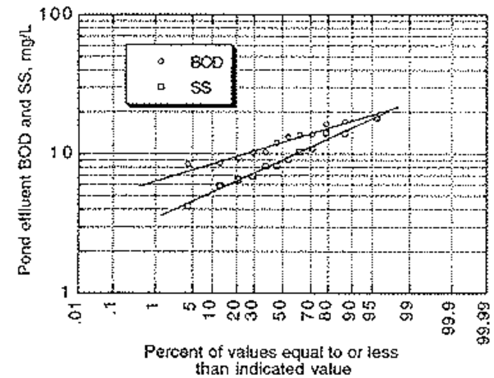


FIGURE 9-14
Performance and stability of water hyacinth system in San Diego.

Water hyacinth growth and harvesting. Water hyacinth plant growth is described in two ways: (1) as the percentage of pond surface covered over a given time period and (2) as the plant density in units of wet plant mass per unit of surface area. Under normal conditions, loosely packed water hyacinths can cover the water surface at relatively low plant densities, about 2 lb/ft² (10 kg/m²) wet weight. Plant densities as high as 16 lb/ft² (80 kg/m²) wet weight can be reached. As in other biological processes, the growth rate of water hyacinths is dependent on temperature. Both air and water temperatures are important in assessing plant vitality. Typical data on the quantity of water hyacinths harvested at Aqua III in San Diego are reported in Table 9-17 (WCPH, 1996).

Process Design Considerations

Objectives of different water hyacinth systems are presented in Table 9-18. Design criteria for water hyacinth systems that are designed to meet the objectives in

TABLE 9-18
Objectives of different types of water hyacinth systems

Type of influent wastewater	Treatment objective	Typical BOD loading rates, lb/ac·d
Primary effluent	Secondary treatment	50–100[*]
Primary effluent	Advanced secondary treatment	250–450[†]
Facultative pond effluent	Secondary treatment	45–90
Secondary effluent	Nutrient removal	10–50

*Organic loading rates at 200 lb/ac·d and more have been used; however, there is increased risk of odors and mosquito nuisance.
† Aeration should be provided for BOD loadings above 100 lb/ac·d.

TABLE 9-19
Typical design criteria and expected effluent quality from nonaerated and aerated water hyacinth wastewater treatment systems*

		Typical design criteria	
Item	Unit	Secondary aerobic (nonaerated)	Secondary aerobic (aerated)
Design parameter			
Influent wastewater		Fine-screened or settled	Fine-screened or settled
Influent BOD_5	mg/L	130–180	130–180
Organic loading rate	lb/ac·d	60–80	250–450
Water depth	ft	1.5–2.5	4–4.5
Detention time	d	10–30	4–8
Hydraulic loading rate	Mgal/ac·d	0.03–0.07	0.16–0.30
Application mode		Step feed	Step feed
Aeration	ft³/min·Mgal	None	400-425
Type of aerator		None	Fine bubble
Channel cross section		Trapezoidal	Trapezoidal
Channel top width†	ft	20–30	20–30
Channel side slopes		1:1	1:1
Channel lining	Type	Geomembrane	Geomembrane
Liner thickness	mil	40–80	40–80
Pond geometry		Horseshoe shape	Horseshoe shape
Recirculation ratio	Qr/Q	0–2	1–2
Water temperature	°C	>10	>10
Harvest schedule		Annually to seasonally	Monthly to weekly
Expected effluent quality‡			
BOD_5	mg/L	<25	<15
TSS	mg/L	<25	<15
TN	mg/L	<20	<15
TP	mg/L	<7	<5

*Adapted in part from WCPH (1996) and WPCF (1989).
†Top width will depend on the method and equipment used to harvest the water hyacinth.
‡Based on typical domestic wastewater and a loading between 80 and 450 lb/ac·d.

Table 9-18 are presented in Table 9-19. Design considerations, including BOD loading rate, water depth, detention time, mosquito control, and vegetation harvesting are discussed below. The design of a water hyacinth system is illustrated in Example 9-8.

BOD loading rate. The range of loading rates for BOD_5 for water hyacinth systems is from 60 to as high as 450 lb/ac·d, depending on the system configuration and whether supplemental aeration is used. At Walt Disney World, Florida, a water hyacinth system without aeration was loaded with primary effluent up to 400 lb/ac·d. Mosquito and odor problems became significant above 200 lb/ac·d. Average loadings on a water hyacinth system should not exceed 100 lb/ac·d unless aeration is used.

Modeling BOD removal kinetics. On the basis of the results of studies conducted at San Diego, it was demonstrated that, for a plug-flow reactor with step feed

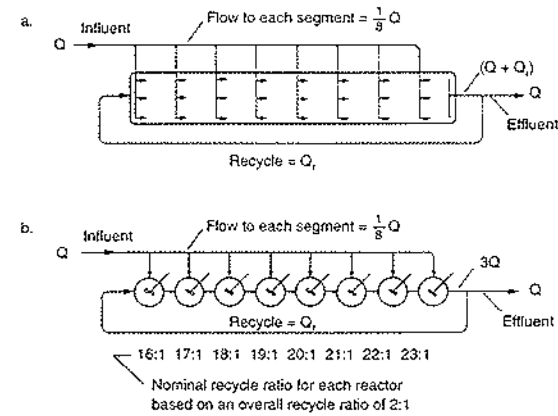


FIGURE 9-15
Schematic for modeling the water hyacinth ponds at San Diego.

and recycle, BOD removal can be modeled by first-order kinetics, assuming each segment of the reactor, corresponding to a feed point, can be modeled as a complete-mix reactor as shown in Fig. 9-15 (Tchobanoglous et al., 1989). The steady-state materials balance for the first complete-mix reactor in the series of eight reactors as shown in Fig. 9-15 is given by

$$\text{Accumulation} = \text{inflow} - \text{outflow} + \text{generation}$$

$$0 = Q_r(C_8) + 0.125Q(C_o) - (Q_r + 0.125Q)(C_1) + (-k_T)(C_1)V_1 \qquad (9\text{-}24)$$

where Q_r = recycle flow, Mgal/d
C_8 = concentration of BOD_5 in effluent from reactor 8 in series, mg/L
$0.125Q$ = inflow to each individual cell ($Q/8$), Mgal/d
C_o = concentration of BOD_5 in influent, mg/L
C_1 = concentration of BOD_5 in effluent from reactor 1 in series, mg/L
k_T = overall first-order removal-rate constant at temperature T, 1/d
V_1 = volume of first reactor in series, Mgal

The estimated value of k_T to be used in the above expression for BOD_5 removal for an aerated water hyacinth system is on the order of 1.95 d^{-1} at 20°C (Tchobanoglous et al., 1989). Other values that have been reported for nonaerated systems in the literature range from 0.7 to about 1.25. The above expression can be used iteratively to check the design of a pond system on the basis of surface loading rate.

Water depth. The critical concern with respect to water depth is to control the vertical mixing in the pond so that the wastewater to be treated will come into contact with the plant roots where the bacteria that accomplish the treatment are located

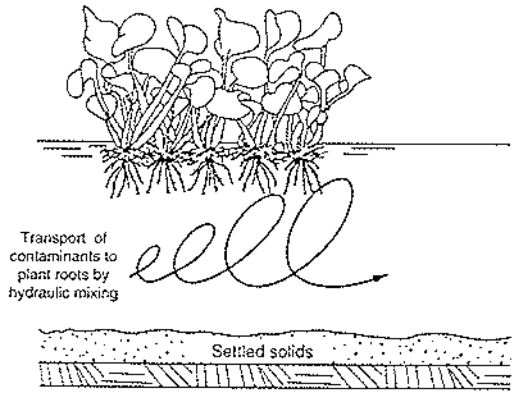


FIGURE 9-16
Water hyacinth roots as sites for bacterial growth.

(see Fig. 9-16). The poor performance observed in some of the early water hyacinth systems was a result of the fact that the operating depth was too deep to promote vertical mixing. Density currents, which allowed the incoming wastewater to flow along the bottom to the outlet with little or no treatment, were also a problem in the early deep systems. Typical operating depths for nonaerated and aerated water hyacinth systems range from 1.5 to 2.5 ft (0.45 to 0.75 m) and 4 to 4.5 ft (1.2 to 1.4 m), respectively. To accommodate variable operating conditions, water hyacinth systems should be designed with an outlet structure that allows the operating depth to be varied.

In aerated water hyacinth systems, greater liquid depths can be used, because the aeration devices also serve as air lift pumps which cause a circulation flow to develop in the pond as shown in Fig. 9-16. The circulation pattern allows the wastewater to come in contact with the plant roots. In addition to the creation of circulation patterns, the added oxygen in aerated systems has made it possible to use organic loading rates 4 times as high as those used for the design of nonaerated systems, successfully. Where aeration devices are used, it is extremely important to use devices that produce fine bubbles, as large bubbles exert a relatively large buoyant force which tends to lift the roots of the water hyacinth plants out of the water column. When fine bubbles are used, the bubbles are intercepted by the roots of the plants. In turn, oxygen is extracted from the air bubble until the buoyant force exceeds the force of adhesion. Where fine-bubble diffusers are used, the measured oxygen transfer efficiency is greater than would be predicted from the operating depth.

Detention time. The detention time needed for BOD removal can be estimated by Eq. (9-6). For systems (duckweed or water hyacinth) in which algae removal is important, a detention time of about 20 days is usually necessary to break the growth cycle of the algae. Aerated water hyacinth systems can perform with detention times of 4 to 10 d, depending on the organic loading and effluent objectives.

Mosquito control. One of the most effective methods for the control of mosquitoes, developed at Aqua II and Aqua III in San Diego, is the use of sprinklers to prevent mosquito ovaposition (WCPH, 1996). The use of sprinklers for the control of mosquitoes is considered in Sec. 9-9. If water sprinkling is to be used for mosquito control, then provisions must be made in the design to account for the water required for spraying.

Vegetation management. The need for water hyacinth harvesting depends on water quality objectives, the growth rates of the plants, mosquito control strategy, and the effects of predators such as weevils. If nutrient removal by plant uptake is a system objective, frequent harvesting is necessary. Design considerations related to water hyacinth harvesting include the type of equipment to be used for harvesting, the required area for storing and processing the harvested plants, and area required for composting, if this method of processing is adopted.

Physical Features of Floating Aquatic Plant Systems Using Water Hyacinths

Physical features of aquatic plant systems include basin configurations, inlet and outlet structures, and aeration. Details of levee and basin construction are available in Stephenson et al. (1980).

Pond configuration. Typical pond configurations used for water hyacinth systems were shown previously in Fig. 9-13. Most of the early water hyacinth systems involved rectangular basins operated in series, similar to stabilization ponds (Figs. 9-13*a*, *b*). In later designs, recycle and step feed (Figs. 9-13*c*, *d*) are employed to (1) reduce the concentration of the organic constituent at the plant root zone, (2) improve the transport of wastewater to the root zone, and (3) reduce the formation of odors. The use of a wraparound design (Fig. 9-13*e*) shortens the required length of the step feed and recycle lines and reduces recycle pumping costs. The wraparound design was also used at Sacramento, California (see Fig. 9-4).

Inlet and outlet structures. Inlet structures range from concrete or wooden weir boxes to manifold pipes with multiple outlets. The objective is to provide a low-maintenance system that will distribute wastewater and solids evenly into the basin without clogging. A subsurface discharge is preferred for inlets, while interbasin and extrabasin transfer structures can be either surface or subsurface. Outlet devices should be located as far from the inlet as possible to avoid short circuiting. If variable operating depths are planned, the outlet should be capable of removing effluent from various depths including periodic draining of the basin.

Supplemental aeration. Water hyacinth systems can benefit from supplemental aeration. If a high-rate system, such as the San Diego water hyacinth system, is selected, the use of aeration with fine-bubble plate diffusers is appropriate (DeBusk et al., 1989).

EXAMPLE 9-8. AQUATIC TREATMENT SYSTEM USING WATER HYACINTHS. A city of 4000 with a STEP-type wastewater collection system is currently connected to an oxidation treatment pond that is overloaded and not meeting its discharge standards of 30 mg/L BOD and TSS. The city has a 4-ac parcel of land. If the per capita flow is 80 gal/d and the BOD is 120 mg/L, determine if the 4-ac parcel is large enough for an effective aerated-type water hyacinth treatment system to upgrade the pond effluent to meet the discharge standards. If the 4-ac parcel is sufficient, lay out a typical water hyacinth system. To accommodate the available harvesting equipment, the maximum width at the top of the water hyacinth ponds should be 26 ft including 1.0 ft of freeboard. Because the ponds will be lined, use a 1:1 side slope. If the removal-rate coefficient is 1.95 d^{-1}, estimate the effluent quality.

Solution

1. Calculate the wastewater flowrate and daily BOD mass loading.
   a. Wastewater flowrate:

$$Q = 4000 \text{ people} \times 80 \text{ gal/capita·d} = 320{,}000 \text{ gal/d}$$
$$= 0.32 \text{ Mgal/d}$$

   b. BOD mass loading rate:

$$\text{BOD, lb/d} = 0.32 \text{ Mgal/d} \times 120 \text{ mg/L} \times 8.34 = 320 \text{ lb/d}$$

2. Select design parameters for the aerated water hyacinth system using the information given in Table 9-19:

   Organic loading rate = 275 lb/ac·d
   Depth = 4 ft
   Maximum width of water surface = 24 ft
   Application mode = step feed with recycle of 1 to 1

3. Determine the required surface area:

$$A = \frac{320 \text{ lb/d}}{275 \text{ lb/ac·d}} = 1.16 \text{ ac}$$

4. Determine the physical characteristics and the volume of the water hyacinth ponds.
   a. Determine the total number of ponds required for a pond length of 300 ft:

$$\text{No. of ponds} = \frac{(1.16 \text{ ac})(43{,}560 \text{ ft}^2\text{/ac})}{(300 \text{ ft})(24 \text{ ft})} = 7$$

   b. Determine the pond bottom width:

$$\text{Bottom width} = 24 \text{ ft} - (2 \times 4) = 16 \text{ ft}$$

   c. Determine the pond volume, neglecting end corrections:

$$V_{\text{Total}} = 7 \times \left(\frac{24 + 16}{2}\right)(4 \text{ ft})(300 \text{ ft}) = 168{,}000 \text{ ft}^3$$
$$= 1.26 \text{ Mgal}$$

5. Determine the detention time:

$$t = \frac{1.26 \text{ Mgal}}{0.32 \text{ Mgal/d}} = 3.94 \text{ d}$$

6. Determine the area required for the pond system, assuming an additional area equal to that for the ponds will be required for access roads and processing facilities.

$$\text{Total area required} = \frac{(7)(24 \text{ ft} + 2 \times 1.0 \text{ ft})(300 \text{ ft})(2)}{43{,}560 \text{ ft}^2\text{/ac}} = 2.5 \text{ ac}$$

   The available 4-ac area is insufficient for a water hyacinth treatment system.

7. Estimate the effluent from the water hyacinth ponds using Eq. (9-24):

$$0 = Q_r(C_8) + 0.125Q(C_o) - (Q_r + 0.125Q)(C_1) + (-k_T)(C_1)V_1$$

   a. Assume the following conditions apply:

   Q_r = recycle flow = 0.32/7 = 0.0457 Mgal/d
   C_8 = assumed concentration of BOD_5 in effluent from reactor 8 in series = 20 mg/L
   $0.125Q$ = inflow to each individual cell (Q/8) = 0.00594 Mgal/d
   C_o = concentration of BOD_5 in influent = 120 mg/L
   C_1 = concentration of BOD_5 in effluent from Reactor 1 in series = unknown, mg/L
   k_T = first-order reaction-rate constant = 1.95 d^{-1}
   V_1 = volume of first reactor in series = $(168{,}000 \text{ ft}^3)/(7 \times 8) = 3000 \text{ ft}^3 = 22{,}440$ gal

   b. Determine the value of C_1:

$$C_1 = \frac{(0.047 \text{ Mgal/d})(20 \text{ mg/L}) + (0.00594 \text{ Mgal/d})(120 \text{ mg/L})}{(0.047 + 0.00594) + (1.95 \times 0.02244)}$$
$$= 17.0 \text{ mg/L}$$

   c. Solving iteratively for C_8 yields a value of about 17 mg/L. Therefore, the effluent from the proposed water hyacinth system will meet the treatment objectives.

9-6 FLOATING AQUATIC PLANT SYSTEMS—DUCKWEED

Floating aquatic plant systems using duckweed have been used in wastewater treatment for a variety of purposes including secondary treatment, advanced secondary treatment, and nutrient removal. The most widely used option for duckweed systems, achieving secondary treatment using enhanced sedimentation, will be the focus of this section.

Process Description

Duckweed systems have been designed primarily to upgrade facultative pond effluents. The process performance and design considerations for duckweed systems are presented in this section.

TABLE 9-20
Nutrient composition of water hyacinths and duckweed grown in wastewater

	Dry weight, %	
Constituent	Water hyacinth	Duckweed
Crude protein	18.1	38.7
Nitrogen (N)	2.9	5.9
Phosphorus (P)	0.6	0.6

Source: WPCF (1989).

Duckweed

Duckweed (*Lemna* spp.) are small freshwater plants with leaves (fronds) that are 0.04 to 0.12 in (1 to 3 mm) in width and roots that are less than 0.4 in (10 mm) long. Duckweed grow faster than water hyacinth (reportedly 30 percent faster) (WPCF, 1989) and are higher in protein (see Table 9-20). Duckweed can form a surface mat on a pond by doubling the area covered in 4 days. The plants do not transfer oxygen into the water, leaving the duckweed pond effluent anoxic. Duckweed are very sensitive to wind drifting and therefore require baffles to keep the plants in place. Duckweed is more cold-tolerant than water hyacinth. Water temperatures of

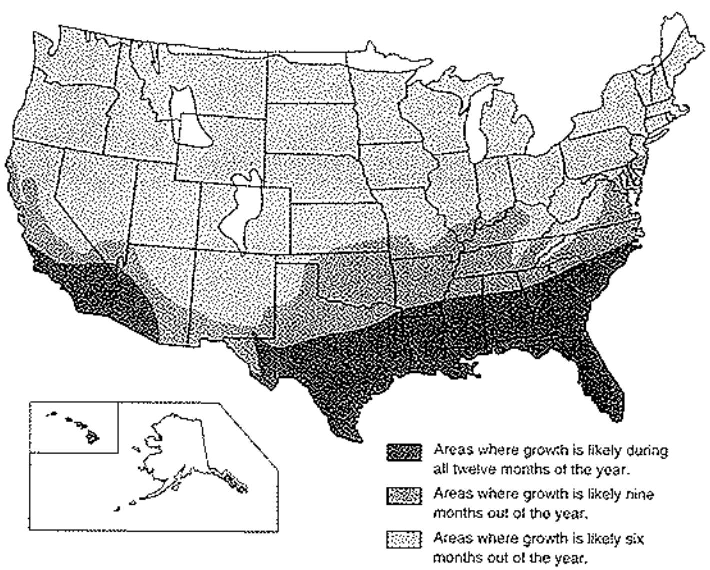


FIGURE 9-17
U.S. zones for the growth of duckweed (adapted from Leslie, 1983).

7°C or higher are needed to sustain the growth. As shown in Fig. 9-17, duckweed can be grown for at least 9 months of the year in temperate climes and 6 months of the year in nearly all U.S. climes.

Constituent Removal and Transformation Mechanisms

Removals of BOD and TSS are generally quite good, with lesser efficiencies demonstrated for nutrients, metals, and pathogens. The operative removal mechanisms are described below.

BOD and TSS removal. BOD removal in duckweed systems occurs as a result of biological activity that is similar to the reactions that occur in facultative ponds. The duckweed cover the surface of the ponds and limit the growth of algae, thereby reducing the oxygen in the water column for aerobic bacterial activity. In addition, the duckweed limits the wind-aided reaeration from the atmosphere, thereby further limiting the BOD removal. As a consequence, the BOD loading should be limited to 25 lb/ac·d (27.5 kg/ha·d) or less.

Nitrogen removal. Nitrogen is removed in aquatic treatment systems by microbial nitrification-denitrification, and to a lesser extent, by plant uptake and harvest. In duckweed systems, denitrification will occur readily; however, nitrification requires an input of oxygen.

Phosphorus removal. Plant uptake and harvest is the pathway for phosphorus removal from duckweed systems.

Metals and trace organics removal. Metal removal mechanisms include plant uptake, chemical precipitation, and adsorption.

Pathogen removal. The removal of entering bacteria and viruses in aquatic plant systems is similar to the mechanisms that are operative in ponds—natural die-off, sedimentation, predation, adsorption, and exposure to ultraviolet light.

Process Performance

Performance expectations for floating aquatic plant systems using duckweed are reviewed in the following discussion.

BOD removal. High levels of BOD and TSS removal are generally expected from duckweed systems. To achieve secondary treatment, most duckweed systems are coupled either with facultative or aerated ponds. In 1995 there were 35 operational wastewater treatment facilities designed specifically as duckweed systems. Most are designed to achieve secondary treatment. The removal of BOD and TSS in duckweed systems is shown in Table 9-21.

TABLE 9-21
Typical effluent BOD and TSS values observed in duckweed systems

Location	Design flow, Mgal/d	Detention time, d	Effluent BOD, mg/L	Effluent TSS, mg/L	Permit*
Arkadelphia, Arkansas	3.0	10	12	15	30/90
Ellaville, Georgia	0.2	20	13	10	20/30
Four Corners, Louisiana	0.16	24	3	3	10/15
Kyle, Texas	0.89	12	18	13	30/30
Mamou, Louisiana	0.8	30	5	8	10/15
Nokesville, Virginia	0.05	12	6	5	12/12
White House, Tennessee	0.8	27	3	4	10/30

*Average BOD/TSS for most stringent season.

Suspended solids removal. The duckweed plants play a major role in the removal of suspended solids. The surface mat blocks the sunlight and the mats enhance sedimentation by creating quiescent conditions. The rate at which the suspended solids settle depends on the nature of the solids. Algal cells take a relatively long period of time (6 to 10 d) to die and begin to settle.

Nitrogen removal. Nitrogen can be removed either by plant uptake and harvesting or by nitrification-denitrification. To remove nitrogen by plant harvest, optimum growth must be achieved and frequent harvest must be accomplished. The density of the plants at the water surface depends on the temperature, availability of nutrients, and frequency of harvest. The typical density on a wastewater pond may range from 0.25 to 0.75 lb/ft^2 (1.2 to 3.6 kg/m^2) (Reed et al., 1995). The optimum growth rate is about 0.1 lb/ft^2·d (0.49 kg/m^2·d).

Annual harvest amounts range from 5.9 to 17.3 ton/ac (13 to 38 mt/ha) with 10 ton/ac (22 mt/ha) being typical. Assuming that the nitrogen content is 5.9 percent of the dry matter, 98 lb/ac·mo of nitrogen can be removed. Assuming that a 12-acre system, 5 ft deep, is used, the harvest of 98 lb/acre·mo of nitrogen in the duckweed would amount to 4.7 mg/L removal of nitrogen from the duckweed pond. Because nitrogen removal via plant harvest is not practical, the Lemna Corporation has developed a submerged media nitrification reactor with supplemental aeration.

Phosphorus removal. Phosphorus removal can be achieved by plant harvest, but only to the same limited extent as for nitrogen. Generally, less than 1 mg/L of phosphorus can be removed by plant uptake and harvest. If wastewater phosphorus concentrations are low and removal requirements are minimal, then harvesting, as practiced in the Devils Lake, North Dakota, system, may be suitable. If significant phosphorus removal is required, however, the use of chemical precipitation with alum, ferric chloride, or other chemicals in a separate treatment step may be more cost-effective.

Metals removal. Duckweed has been shown to accumulate 27 μg zinc, 10 μg lead, and 5.5 μg nickel per mg of duckweed when exposed to 10 mg/L of the three metals. Because the metals concentrations in municipal wastewater are very low, the metals concentrations in duckweed are similarly low.

TABLE 9-22
Typical design criteria and expected effluent quality for duckweed systems

Item	Unit	Value
Design parameter		
Influent wastewater		Facultative pond effluent
BOD loading rate	lb/ac·d	20–25
Detention time	d	20–30
Water depth	ft	5–8
Hydraulic loading rate	gal/ac·d	<55,000
Harvest schedule		Monthly for secondary treatment, weekly for nutrient removal
Expected effluent quality*		
Secondary treatment		
BOD_5	mg/L	<30
TSS	mg/L	<30
TN	mg/L	<15
TP	mg/L	<6
Nutrient removal		
BOD_5	mg/L	<10
TSS	mg/L	<10
TN	mg/L	<5
TP	mg/L	<2

*Expected effluent quality based on loadings equal to or less than given values.

Process Design Considerations

Process design criteria and expected water quality for duckweed systems are presented in Table 9-22. Design considerations include detention time, BOD loading rates, and water depth.

Detention time. For duckweed systems in which algae removal is important, a detention time of about 20 days is usually necessary to break the growth cycle of the algae.

BOD loading rate. The range of loading rates for BOD_5 is from 20 to 25 lb/ac·d for duckweed systems. The Lemna Corporation, which offers proprietary floating plastic barriers (see Fig. 9-18) and harvesting equipment (see Fig. 9-19), suggests that wastewater entering the duckweed portion of the facility be partially treated to a BOD level of 60 mg/L or less by facultative ponds, aerated ponds, or mechanical treatment plants. To achieve a 20-mg/L BOD in the effluent, Lemna suggests a target influent of 40 mg/L, 20-d detention time, and a pond sizing of 12 ac/Mgal·d (12.8 m^2/m^3·d), based on a minimum pond depth of 5 ft (1.5 m). To achieve a final BOD of 10 mg/L, it is suggested that a target influent BOD of 30 mg/L, a 28-d hydraulic detention time, and a pond sizing of 17.5 ac/Mgal·d) (18.4 m^2/m^3·d) be used.

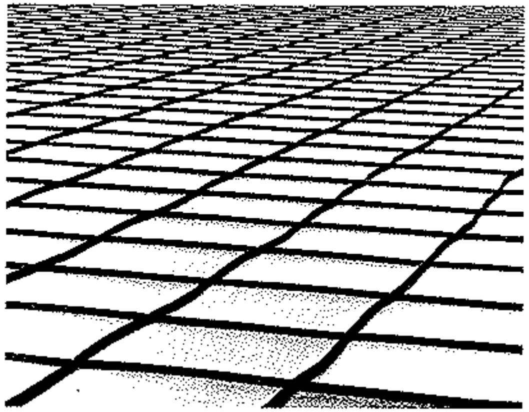


FIGURE 9-18
Floating plastic barriers for control of duckweed.

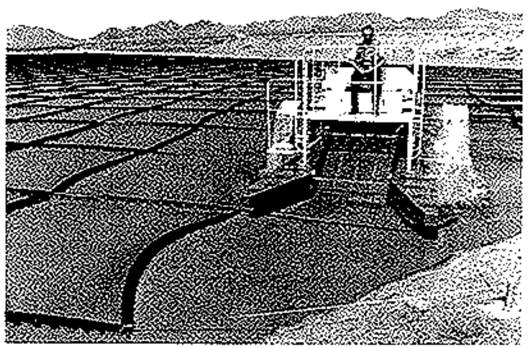


FIGURE 9-19
Floating harvester used to harvest duckweed.

Water depth. With duckweed the depth can be 5 to 8 ft (1.5 to 2.4 m) or deeper because there is no root-bacteria contact to be achieved.

Physical Features of Floating Aquatic Plant Systems Using Duckweed

Physical features of aquatic plant systems using duckweed include basin configurations and inlet and outlet structures. Details of levee and basin construction are available in Stephenson et al. (1980).

Basin configurations. Duckweed ponds can be designed like water hyacinth basins or as large ponds with floating baffles. Floating baffles are used to reduce the effects of the wind. Long narrow basins can also be used, and emergent plants can be added to avoid wind effects.

Inlet and outlet structures. Inlet structures range from concrete or wooden weir boxes to manifold pipes with multiple outlets. The objective is to provide a low-maintenance system that will distribute wastewater and solids evenly into the basin without clogging. A subsurface discharge is preferred for inlets, while interbasin and extrabasin transfer structures can be either surface or subsurface. Outlet devices should be located as far from the inlet as possible to avoid short circuiting. If variable operating depths are planned, the outlet should be capable of removing effluent from various depths, including periodic draining of the basin.

9-7 COMBINATION SYSTEMS

There are a number of systems that combine natural treatment processes. The earlier meadow-marsh-pond system demonstrated on Long Island in the 1970s led to combinations of overland flow and constructed wetlands and to combinations of aquatic plant pond systems with constructed wetlands. The solar aquatic system at Harwich, Massachusetts (see Chap. 14), is an example of the latter combination for the treatment of septage.

Frederick, Maryland

The Advanced Ecologically Engineered System (AEES) at Frederick, Maryland, is one of several related projects in the United States intended to provide advanced treatment of municipal wastewater. The AEES technology is also called a "Living Machine" by Dr. John Todd, who developed the concept. The facility at Frederick was constructed in 1993 and treated 40,000 gal/d of screened and degritted wastewater. The schematic flow diagram and several views of the system are presented in Fig. 9-20. The detention time was 3.6 d through the system (Reed et al., 1996). Approximately 85 percent of the BOD removal in the system was accounted for in the anaerobic upflow filter. Performance data for the system are presented in Table 9-23.

Benton, Kentucky

A constructed wetland system at Benton, Kentucky, was designed for the removal of BOD, TSS, and ammonia from an existing treatment pond. When ammonia removal fell short of expectations, a retrofit design was proposed by Reed (Reed et al., 1995). The design involved the addition of a recirculating gravel filter capable of nitrifying the wastewater. The nitrified effluent was then reintroduced into the constructed wetland to accomplish the denitrification step. Design factors and process performance data are presented in Table 9-24.

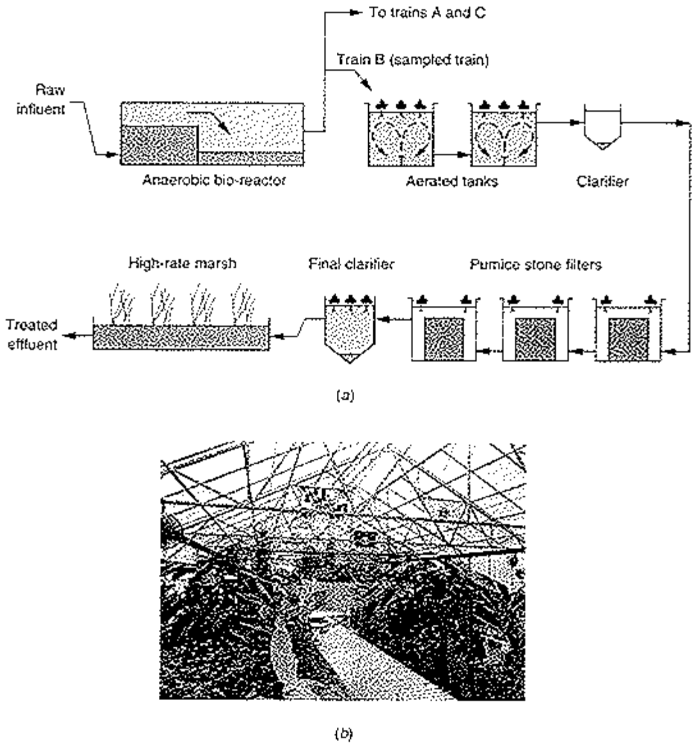


FIGURE 9-20
Frederick, Maryland, aquatic treatment system: (*a*) flow diagram and (*b*) view of treatment system inside greenhouse. High-rate marsh is shown in the foreground. Anaerobic bio-reactor is shown in Fig. 7-50 in Chap. 7.

TABLE 9-23
Performance data for the Frederick, MD Living Machine, March 1995 to March 1996[a]

Item	Unit	Process value	Observed mean value
BOD_5	mg/L	≤ 10	4.8
COD (total)	mg/L	≤ 50	27
TSS	mg/L	≤ 10	1.4
NH_4-N	mg/L	≤ 1	1.7
NO_3-N	mg/L	≤ 5	7.0
Nitrogen (total)	mg/L	≤ 10	10.6
Phosphorus (total)	mg/L	≤ 3	6.0

[a] From Living Technologies, Inc (1997).

TABLE 9-24
Design parameters and performance data for recirculating gravel filter at Benton, Kentucky[a]

Item	Unit	Value
Design parameter		
Flowrate	Mgal/d (m^3/d)	1.0 (3785)
Medium size	in (mm)	0.25 (7)
Medium depth	ft (m)	2 (0.6)
Hydraulic loading rate	gal/ft²·d (m/d)	140 (5.7)
Ammonia loading	m²/kg·d	1230
Recirculation ratio		3–1
Wastewater temperature	°C	12–19
Effluent quality[b]		
TKN influent	mg/L	10–20
TKN effluent	mg/L	1.4–4
Ammonia removal	%	77

[a] Adapted from Askew et al. (1994).
[b] Expected effluent quality based on loadings equal to or less than given values.

9-8 DESIGN PROCEDURES FOR CONSTRUCTED WETLANDS

Design considerations and overall design procedures are considered in this section. Design procedures for constructed wetlands and floating aquatic plant systems are presented in Table 9-25.

Process Design Procedure for FWS Wetlands

The procedure for process design of FWS constructed wetlands involves the following steps:

1. Determine the limiting effluent requirements for BOD, TSS, and nitrogen or phosphorus.
2. Determine the allowable effluent BOD by subtracting 5 mg/L for BOD related to plant decay.
3. Select an appropriate apparent BOD removal-rate constant and correct for the critical temperature.
4. Calculate the detention time to achieve the desired level of BOD removal.
5. Alternatively, if nearby performance data are available, determine the coefficient of reliability (COR) for the percent reliability required, and calculate the k value for the overall BOD removal required. Use Eq. (9-6) to determine the required detention time.
6. If BOD and TSS are the only parameters to be removed, the organic loading rate should be checked, and the larger of the two areas should be selected.
7. Determine the detention time required for nitrogen or ammonia removal.

TABLE 9-25
Principal steps in the design of constructed wetlands and aquatic plant systems

FWS wetlands	SF wetlands	Water hyacinths	Duckweed
Define treatment requirements	Define treatment requirements	Define treatment requirements	Define treatment requirements
Characterize wastewater	Characterize wastewater	Characterize wastewater	Characterize wastewater
Gather background information	Gather background information	Gather background information	Gather background information
Site evaluation	Site evaluation	Site evaluation	Site evaluation
Determine pretreatment level	Determine pretreatment level	Determine pretreatment level	Determine pretreatment level
Select vegetation	Select vegetation	Determine design parameters	Determine design parameters
Determine design parameters	Determine design parameters	Vector control measures	Detailed design of system
Vector control measures	Detailed design of system components	Detailed design of system	Determine monitoring requirements
Detailed design of system components		Determine monitoring requirements	
Determine monitoring requirements			

8. Select the largest detention time for design, based on the limiting design parameter.
9. Determine the required area. Increase the area by 15 to 25 percent for a factor of safety.
10. Select an aspect ratio consistent with the site constraints and determine the dimensions of the wetland.
11. Check the headloss to ensure adequate head between the influent and effluent ends.

Process Design Procedure for SF Wetlands

The procedure for process design of SF constructed wetlands involves the following steps:

1. Determine the limiting effluent requirements for BOD, TSS, and nitrogen. Reduce the target effluent values by the expected plant decay concentrations.
2. Determine the detention time using first-order kinetics with plug flow.
3. Calculate the required area for nitrogen or ammonia removal.
4. Determine the field area for the SF bed, based on the largest required detention time. Increase the area by 15 to 25 percent for a factor of safety.

5. Calculate the cross-sectional area needed to hydraulically accept the flow, using Darcy's law.
6. Once the cross-sectional area has been determined, calculate the width by dividing the area by the depth.
7. Calculate the bed length to achieve the needed surface area of the bed.
8. Check the bed dimensions for reasonableness. The length-to-width ratio can range from 0.2:1 up to 2:1. Adjust the length or width as necessary to ensure a reasonable length, in case of heavy precipitation.

9-9 MANAGEMENT OF CONSTRUCTED WETLANDS AND AQUATIC SYSTEMS

Operation and maintenance considerations in the management of constructed wetlands and floating aquatic plant systems are described in this section.

Management of Constructed Wetlands

Issues involved in the management of FWS wetlands include mosquito control, vegetation harvesting, wildlife considerations, and monitoring. For SF wetlands the wildlife and monitoring elements apply, and vegetation management is included.

Mosquito control. With FWS wetlands mosquito control is essential. The provisions cited for mosquito control in water hyacinth systems are also applicable to FWS constructed wetlands, including stocking with mosquitofish, maintenance of aerobic conditions, use of biological controls, and the encouragement of predators. At Arcata, California, the FWS wetland actually produces less mosquito larvae than the previous unused marshy area because of the encouragement of habitat for swallows and mosquitofish.

At Sacramento County, the following combination of management techniques has been successful in controlling mosquitoes (Williams et al., 1996):

1. Mosquitofish stocking.
2. Daily monitoring for mosquito larvae from April through October.
3. Applications of *Bacillus thuringensis israelensis* (Bti) when needed.
4. Vegetation management to maintain open water and pathways for mosquitofish to get to the mosquito larvae.

Vegetation harvesting. Harvesting of the emergent vegetation is practiced to maintain hydraulic capacity, promote active growth, and avoid mosquito growth. Harvesting for nutrient removal is not practical and is not recommended. Harvesting will affect performance, so the harvested cell should be taken out of service before and for several weeks after harvesting. Harvested vegetation can be burned, chopped and composted, chopped and used as mulch, or digested (Hayes et al., 1987). A vegetation control strategy for a typical FWS wetlands is presented in Table 9-26.

TABLE 9-26
Vegetation control strategy for FWS constructed wetlands*

Issue	Outcome
Operating goal	Process performance
Problem identification	Clogging of flow paths, odors from decomposition, short circuiting, low density, poor plant health
Causative factors	Aggressive growth, lack of vegetative management, excessive water depth, poor water flow patterns, seasonal variation, grazing
Management strategies	Reduce water depth, soil enhancement, supplemental planting, controlled burns, periodic harvesting
Lead time	Growing season
Evaluation of control	Vegetation surveys, vegetation maps, photographic records

*Adapted from Tchobanoglous (1993).

Wildlife considerations. Wildlife, including ducks, shorebirds, raptors, field birds, deer, jackrabbits, and muskrats will be attracted to wetlands. In Florida, alligators and snakes have been reported in constructed wetlands. Ducks need open water, which may not be compatible with the need for thick vegetation to achieve secondary treatment. Burrowing animals, such as nutria, can also create problems with berms (Crites and Lesley, 1997). If wildlife habitat enhancement is a project goal, islands raised above deeper water should be considered. These habitat islands can support upland vegetation and provide nesting trees for birds (Wilhelm et al., 1989).

Monitoring. Monitoring needs can include flow, surface water quality, and groundwater quality. Variable-height weirs can be used to monitor flow out of the wetland and to provide a convenient sampling point. Surface water sampling points should be located at catwalks or boardwalks to allow sampling without disturbing the flow. A summary of suggested monitoring parameters is presented in Table 9-27.

Vegetation management for SF wetlands. Harvesting is not necessary for SF wetland vegetation; however, development of the roots into the media is important. After initial establishment, the water level needs to be dropped so that the roots will extend, eventually to the bottom of the media.

Management of Floating Aquatic Plant Systems

Both water hyacinth and duckweed systems require management to avoid odors and to harvest the plants. For water hyacinth systems the management issues are mosquito control, vegetation harvesting, and sludge removal. For duckweed systems the issues are vegetation harvesting and sludge management. Mosquito problems with duckweed systems do not occur because the pond surface is effectively sealed off by the plants, and the female mosquitoes cannot reach the water to lay their eggs.

TABLE 9-27
Summary of suggested monitoring parameters for constructed wetlands*

Parameter	Project phase (Pre- or during construction or ongoing)	Location	Frequency of collection
Water quality[1,2]			
Dissolved oxygen	Ongoing	In, out, along profile	Weekly
Hourly dissolved oxygen	Ongoing	Selected locations	Quarterly
Temperature	Pre, ongoing	In, out, along profile	Daily/weekly
Conductivity	Pre, ongoing	In, out	Weekly
pH	Pre, ongoing	In, out	Weekly
BOD	Pre, ongoing	In, out, along profile	Weekly
SS	Pre, ongoing	In, out, along profile	Weekly
Nutrients	Pre, ongoing	In, out, along profile	Weekly
Chlorophyll A	Ongoing	Within wetland, along profile	Annually
Metals (Cd, Cr, Cu, Pb, Zn)	Pre, ongoing	In, out, along profile	Quarterly
Bacteria (total and fecal coliform)	Pre, ongoing	In, out	Monthly
EPA priority pollutants	Pre, ongoing	In, out, along profile	Annually
Other organics	Pre, ongoing	In, out, along profile	Annually
Biotoxicity	Pre, ongoing	In, out	Semiannually
Sediments			
Redox potential	Pre, ongoing	In, out, along transects	Quarterly
Salinity	Pre, ongoing	In, out, along transects	Quarterly
pH	Pre, ongoing	In, out, along transects	Quarterly
Organic matter	Pre, post	In, out, along transects	Quarterly
Vegetation			
Plant coverage	Ongoing	Within wetland, along transects	Quarterly
Identification of plant species	Ongoing	Within wetland, along transects	Annually
Plant health	Ongoing	Within wetland	Observe weekly

(continued)

TABLE 9-27
(Continued)

Parameter	Project phase (Pre- or during construction or ongoing)	Location	Frequency of collection
Biota			
Plankton (zooplankton tow)	Ongoing	Within wetland, along transects	Quarterly
Invertebrates	Ongoing	Within wetland, along transects	Annually
Fish	Ongoing	Within wetland, along transects	Annually
Birds	Pre, ongoing	Within wetland, along transects	Quarterly
Endangered species	Pre, during, ongoing	Within wetland, along transects	Quarterly
Mosquitoes	Pre, during, ongoing	Within wetland, selected locations	Weekly during critical months
Wetland development			
Flowrate	Ongoing	In, out	Continuous
Flowrate distribution	Ongoing	Within wetland	Annually
Water surface elevations	Ongoing	Within wetland	Semiannually
Marsh surface elevations	Ongoing	Within wetland	Quarterly

[a] Adapted from Tchobanoglous (1993).
[b] Water quality for pre- and during construction refers to the wastewater that is to be applied to wetland.
[c] Permitting agencies may not require all parameters to be tested, or to be tested at the same frequency.

Mosquito control. In many areas of the United States, the propagation of mosquitoes in aquatic systems may be the critical factor in their acceptance or rejection. A typical vector control strategy is outlined in Table 9-28. The objective of mosquito control is to suppress mosquito populations below the threshold level required for disease transmission or nuisance tolerance levels. Strategies that have been used to control mosquito populations include (WCPH, 1996):

1. Stocking ponds with mosquitofish (*Gambusia* spp.).
2. More effective pretreatment to reduce the total organic loading on the aquatic system, to help maintain aerobic conditions.
3. Step feed of influent waste stream with recycle (see Fig. 9-13).
4. More frequent plant harvesting.
5. Water spraying in the evening hours (see Fig. 9-21).
6. Application of chemical control agents (larvicides).
7. Diffusion of oxygen (with aeration equipment).
8. Biological control agents (e.g., Bti).

Fish used for control of mosquitoes (typically *Gambusia* spp.) will die under the anaerobic conditions that exist in organically overloaded ponds. In addition to inhibited fish populations, mosquitoes may develop in dense water hyacinth systems

TABLE 9-28
Operational issue—vector control strategy for water hyacinth treatment systems

Issue	Outcome
Operating goal	Control of mosquitoes
Problem identification	Increased counts in resting box, emergence traps, dip samples
Causative factors	Execessive plant growth, lack of predators
Management strategies	Draw water surface down, use biological controls, use conventional controls (Bear oil 2000, Bti)
Lead time	2 to 3 weeks, depending on sampling frequency
Evaluation of control	Reduced larval count

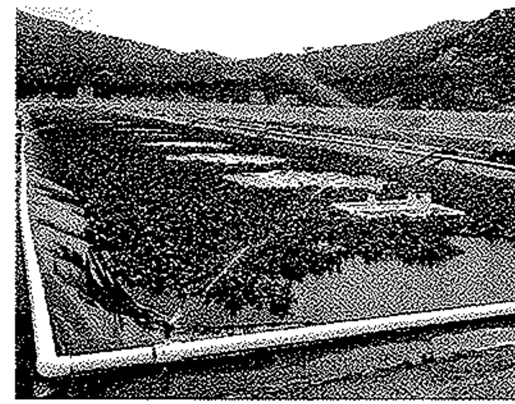


FIGURE 9-21
Sprinkler system used to control the breeding and production of mosquitoes.

when plants have been allowed to grow tightly together. Pockets of water form as the plants bridge together that are accessible to the mosquitoes but not the fish.

One of the most effective methods for the control of mosquitoes, developed at Aqua II and Aqua III in San Diego, is the use of sprinklers to prevent mosquito oviposition. For example, *Culex* spp. mosquitoes oviposit on still bodies of water and require about 20 to 35 minutes to complete oviposition. The use of sprinklers both disrupts mosquito flight patterns and effectively reduces oviposition by disturbing or killing the female mosquitoes before or shortly after they have landed. The sprinklers are operated from about 8 P.M. to 6 A.M. The sprinkler coverage pattern is shown in Fig. 9-21 (WCPH, 1996).

Vegetation management in hyacinth systems. At Aqua III, water hyacinths are harvested by a truck-mounted hydraulic crane with an 85-ft boom and

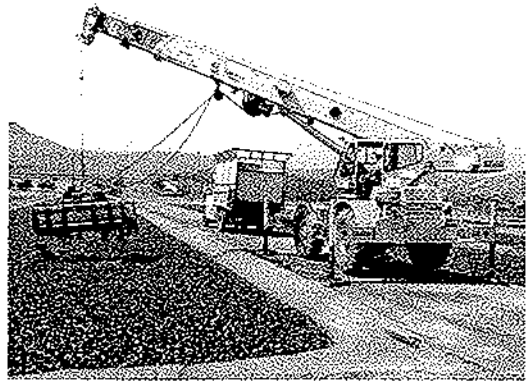


FIGURE 9-22
Articulated clamshell for harvesting water hyacinths.

a 5-ft open type clamshell (Fig. 9-22). Harvested water hyacinths are composted on site. Because high moisture content tends to reduce the effectiveness of the compost process, the harvested water hyacinths are chopped by a tub grinder (see Fig. 9-23) and spread out in a thin layer to reduce the moisture content before composting (see Fig. 9-24). After about 5 d, when the moisture content has been reduced to about 60 percent, the water hyacinths are formed into windrows for the composting process.

No bulking agent is required and temperatures greater than 160°F can be maintained for 15 d, without the addition of supplementary moisture. The overall

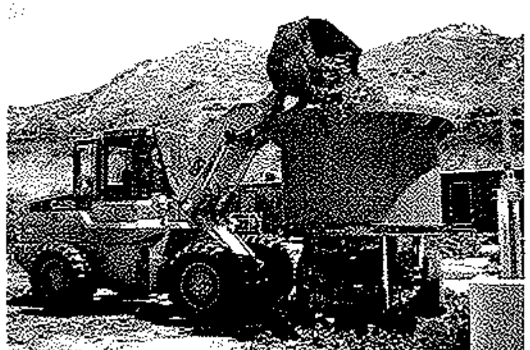


FIGURE 9-23
Tub grinder used to chop water hyacinths for predrying before composting.

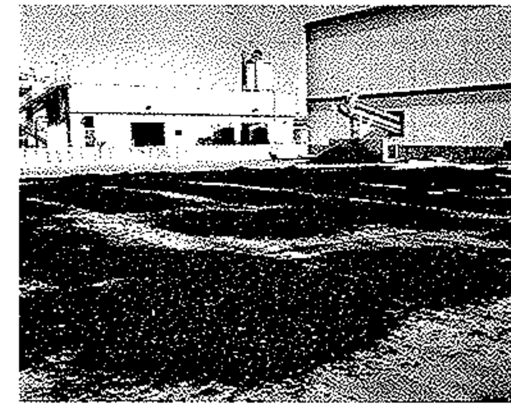


FIGURE 9-24
Water hyacinth spread out to dry, to reduce the initial moisture content before composting in windrows.

volume reduction, brought about by processing, drying, and comp
the volume of the newly harvested wet water hyacinths and the
compost remaining after the composting process, has averaged 99
reduction of 100 to 1) (WCPH, 1996). Such a high volume reduct
because the water hyacinths contain little lignin, and both bacte
organisms are involved in the composting process. The final com
US EPA 503 pathogen and metals requirements for Class A co
1996).

Sludge management in hyacinth systems. The solids tha
aquatic systems include plant detritus, inorganic solids, and biologic
solids are usually removed infrequently (annually or less frequen
Sludge accumulation in the San Diego water hyacinth system avera
13 months of operation (Tchobanoglous et al., 1989).

Duckweed management. The need for duckweed harvesting
ter quality objectives and the growth rates of the plants. Monthly harv
during the growing season. If nutrient removal by plant uptake is a sy
harvesting frequencies as high as once per week may be required. N
tematives for harvested duckweed include composting, use as anima
application.

Sludge management in duckweed systems. The solids tha
aquatic systems include plant detritus, inorganic solids, and biologic
solids are usually removed infrequently (annually or less frequently

9-10 EMERGING TECHNOLOGIES

Emerging technologies are those that have shown promise in small research and demonstration projects. These include vertical-flow wetlands, batch-flow wetlands, submerged vegetation aquatic plant systems, and algal turf scrubbers.

Vertical-Flow Wetlands

In vertical-flow constructed wetlands the applied water flows through the gravel bed in a manner similar to flow in a planted rapid infiltration system. During the loading period, air is forced out of the bed; during the drying period, atmospheric air is drawn into the bed, which increases oxygenation of the bed. Diffusion of atmospheric oxygen into the bed is rapid because the diffusion of oxygen is approximately 10,000 times faster in air than in water. Vertical-flow wetlands have been used in Europe and in reed bed treatment and dewatering of biosolids (Brix, 1993).

Batch-Flow Wetlands

Batch-flow wetlands and aquatic plant systems have the same appeal as vertical-flow wetlands. Both are attempts to increase the oxygen levels in the root zone and detritus areas in the beds. Batch-flow wetlands (8 d of filling and 2 d emptying) are being tested at Sacramento Regional County Sanitation District (Crites et al., 1996).

Submerged Vegetation Aquatic Plant Systems

Submerged vegetation has been studied by various researchers (Kozak and Bishop, 1987; Eighmy et al., 1987). Previous efforts were limited by the need to aerate the vegetated ponds. Recent research at Contra Costa County shows promise for nitrifying secondary effluent (Bouey, 1996).

Algal Turf Scrubbers

The algal turf scrubber is an attempt to grow and harvest attached-growth algae (periphyton) for nutrient removal. The device has been operated in pilot studies for phosphorus removal in the Everglades nutrient removal project and at Patterson, California.

PROBLEMS AND DISCUSSION TOPICS

9-1. Constructed wetlands can be designed by using a first-order equation based on detention time or by using surface area loading rates. Compare and contrast these two methods for the design.

9-2. An FWS wetland is designed to treat 0.15 Mgal/d of facultative treatment pond effluent from a BOD of 80 mg/L to a BOD of 20 mg/L. Determine the detention time and net field area required for treatment. Use a water depth of 12 in. Use a water temperature of 20°C.

9-3. An FWS wetland is proposed to treat either lagoon effluent (minimum temperature of 5°C) or an Imhoff tank effluent (minimum temperature of 8° C). Compare needed detention times for 85 percent BOD removal.

9-4. A secondary effluent needs 85 percent ammonia removal. If the ammonia nitrogen concentration is 20 mg/L in the secondary effluent, calculate the hydraulic loading rate needed for a FWS wetland. If the wetland water depth is 4 in, what is the detention time?

9-5. For the two temperatures in Prob. 9-3, calculate the detention time needed for 80 percent nitrogen removal by water hyacinths.

9-6. Using the following data from a Gustine, California, FWS wastewater treatment system, determine the coefficient of reliability for 92 percent.

	BOD, mg/L	
Month	1994	1995
January	18	15
February	9	15
March	12	10
April	17	8
May	24	10
June	19	15
July	26	18
August	21	29
September	23	26
October	29	25
November	25	29
December	30	24

9-7. Using the following data from a San Diego water hyacinth wastewater treatment system, determine the coefficient of reliability for 99 percent.

Month	BOD, mg/L
January	8.4
February	10.2
March	17.9
April	10.3
May	13.2
June	9.3
July	8.6
August	12.0
September	13.7
October	13.8
November	16.3
December	17.0