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Chapter 16

Constructed Wetlands for Wastewater Treatment: Principles and Practices

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Abstract. Constructed wetlands (CW), either free water surface or subsurface flow type, are natural treatment systems which employ activities of microbes, media or plants, in waste stabilization without the aid of mechanical or energy-intensive equipment. CW can significantly reduce biochemical oxygen demand (BOD_5), suspended solids (SS), and nitrogen, as well as metals, trace organics, and pathogens. The basic treatment mechanisms include sedimentation, chemical precipitation and adsorption, and microbial interactions with BOD_5, SS and nitrogen, as well as some uptake by the vegetation. The process stability under varying environmental conditions, lower construction and operating costs, and the possibility to create a wildlife habitat, in the case of FWS systems are advantages over the conventional wastewater treatment systems. The factors affecting wastewater treatment efficiency of CW are the area of CW, depth, porosity of the material, type of plants which transfer oxygen to the bulk through roots, hydraulic budget, site selection, flow pattern. Two operational considerations associated with wetlands for wastewater treatment are mosquito control and plant harvesting.

16.1. Introduction

Wetlands are areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to maintain saturated conditions (U.S. EPA, 1988). They are comparatively shallow (typically less than 0.6 m) bodies of slow-moving water in which dense stands of water-tolerant plants such as cattails, bulrushes, or reeds are grown. In man-made systems, these bodies are artificially created and are typically long, narrow trenches or channels.

Constructing a wetland where one did not exist before avoids many of the environmental concerns and user conflicts associated with natural wetlands and allows design of the wetland for optimum wastewater treatment. Unlike natural wetlands, which are confined by availability and proximity of the wastewater

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source, constructed wetlands (CW) can be built almost anywhere, including lands with limited uses. Typically, a CW should perform better than a natural wetland of equal area since the bottom is usually graded and the hydraulic regime in the system is controlled. Process reliability is also improved because the vegetation and the other system components can be managed as required (Reed et al., 1988).

16.2. Types and Functions of Constructed Wetlands

CW are classified into two types: free water surface (FWS) systems with shallow water depths and subsurface flow (SF) or vegetated submerged bed (VSB) systems with water flowing laterally through the sand or gravel.

16.2.1. Free Water Surface Systems

These systems typically consist of basins or channels, with a natural or constructed subsurface barrier of clay or impervious geotechnical material to prevent seepage, soil or another suitable medium to support the emergent vegetation, and water at a relatively shallow depth flowing over the soil surface (Fig. 1). The shallow water depth, low flow velocity and presence of the plant stalks and litter regulate water flow and, especially in long, narrow channels, ensure plug-flow conditions to minimize short-circuiting (U.S. EPA, 1988).

16.2.2. Subsurface Flow (SF) Systems

An SF system typically consists of a trench or a bed underlain by impermeable material to prevent seepage and containing a medium that supports the growth of

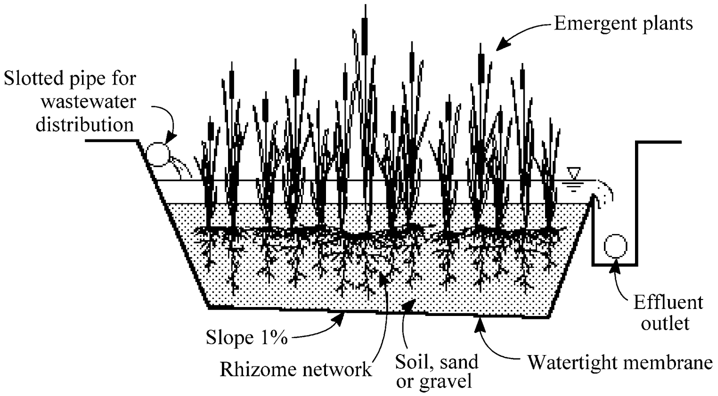


Figure 1: Free water surface (FWS) system.

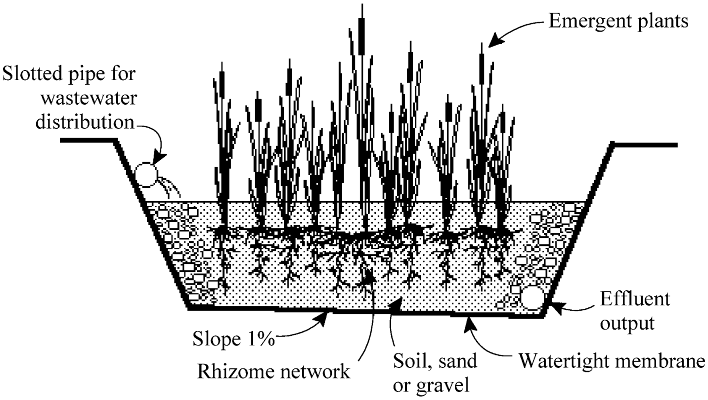


Figure 2: Subsurface flow (SF) system.

emergent vegetation (Fig. 2). The media used have included rock or crushed stone (10–15 cm diameter), gravel, and different soils, either alone or in various combinations (Reed et al., 1988). The wastewater flows laterally through the medium and is purified during the contact with the surfaces of the medium and the root zone of the vegetation. This subsurface zone is continuously saturated and therefore is generally anaerobic. However, the plants can convey an excess of oxygen to the root system, so there are aerobic microsites adjacent to the roots and rhizomes.

16.2.3. Advantages and Disadvantages

CW offer several potential advantages as a wastewater treatment process. These potential advantages include site location flexibility, less rigorous pre-application treatment, no alteration of natural wetlands, simple operation and maintenance, process stability under varying environmental conditions, lower construction and operating costs, and in the case of FWS systems, the possibility to create a wildlife habitat. The potential problems with FWS CW include mosquitoes. Start-up problems in establishing the desired aquatic plant species can be a problem with FWS and SF wetlands alike (U.S. EPA, 1988; Bastian et al., 1989).

16.3. Types and Functions of Vegetation

The major benefit of plants in CW is the transferring of oxygen to the root zone. The plant roots in the system penetrate the soil or support medium, and transport oxygen deeper than it would naturally travel by diffusion alone.

Perhaps most important in the FWS wetlands are the submerged portions of the leaves, stalks, and litter, which serve as the substrate for attached microbial

Table 1: Emergent aquatic plants for wastewater treatment.

Common name	**Scientific name**	**Temperature (°C)**		**Maximum salinity tolerance (ppt[a])**	**Root penetration (cm)**	**Effective pH range**
		Desirable	**Seed germination**			
Cattail	*Typha* spp.	10–30	12–24	30	30	4–10
Common reed	*Phragmites communis*	12–23	10–30	45	60	2–8
Rush	*Juncus* spp.	16–26	–	20	–	5–7.5
Bulrush	*Scirpus* spp.	16–27	–	20	76	4–9
Sedge	*Carex* spp.	14–32	–	–	–	5–7.5

Modified from U.S. EPA (1988).
[a] ppt denotes parts per thousand.

growth. It is the responses of this attached biota that is believed responsible for much of the treatment that occurs.

The emergent plants most frequently found in wastewater wetlands include cattails, reeds, rushes, bulrushes and sedges. It is estimated that these plants transfer 5–45 g O_2/day/m^2 depending on plant density and oxygen stress levels in the soil (Reed et al., 1988). Table 1 lists some of the major environmental requirements of each as well as their maximum depths of root penetration.

16.4. Wastewater Treatment Mechanisms

Wetland systems can significantly reduce biochemical oxygen demand (BOD_5), suspended solids (SS), and nitrogen, as well as metals, trace organics, and pathogens. The basic treatment mechanisms include sedimentation, chemical precipitation and adsorption, and microbial interactions with BOD_5, SS and nitrogen, as well as some uptake by the vegetation (U.S. EPA, 1988).

16.4.1. BOD Removal

The removal of settleable organics is very rapid in all wetland systems and is due to the quiescent conditions in the FWS systems, and to deposition and filtration in the SF systems.

In FWS wetlands, removal of the soluble BOD is mainly due to the attached microbial growth. The major source of oxygen for these reactions is reaeration at the water surface, since algae are typically not present. Any excess oxygen transmitted by the plant to the root zone is likely to be consumed in the soil profile and not to contribute significantly to oxygen levels in the water. Wind-induced water turbulence and mixing will also be reduced or eliminated if a dense stand of vegetation is present.

The major oxygen source for the subsurface components (soil, gravel, rock and other media, in trenches or beds) are the gases transmitted by the vegetation to the root zone. In most cases the system is designed to maintain flow below the surface of the bed, so there can be very little direct atmospheric reaeration. The selection of plant species can therefore be an important factor.

Table 2 reports the removal efficiencies of BOD_5 and SS from CW in Canada, U.S.A. and Australia.

16.4.2. Suspended Solids Removal

SS removal is very effective in both types of CW (see Table 2). Most of the removal occurs within the first few meters beyond the inlet, owing to the quiescent conditions and the shallow depth of liquid in the system. Controlled dispersion of

Table 2: Summary of BOD_5 and SS removal from constructed wetlands.

Project	**Flow (m^3/day)**	**Wetland type**	**BOD_5 (mg/l)**		**SS (mg/l)**		**% Reduction**		**Hydraulic surface loading rate (m^3/ha/day)**
			Inf.	**Eff.**	**Inf.**	**Eff.**	**BOD_5**	**SS**	
Listowel, Ontario	17	FWS[a]	56	10	111	8	82	93	–
Santee, CA	–	SF[b]	118	30	57	5.5	75	90	–
Sydney, Australia	240	SF	33	4.6	57	4.5	86	92	–
Arcata, CA	11,350	FWS	36	13	43	31	64	28	907
Emmitsburg, MD	132	SF	62	18	30	8.3	71	73	1,543
Gustine, CA	3,785	FWS	150	24	140	19	84	86	412

U.S. EPA (1988).
[a] Free water surface system.
[b] Subsurface flow system.

the influent flow with proper diffuser pipe design can help to ensure low velocities for solids removal, and even loading of the wetland so that anoxic conditions are prevented at the upstream end of the channels.

16.4.3. Nitrogen Removal

Nitrogen is mainly removed by nitrification/denitrification. Other removal mechanisms include plant uptake and volatilization as ammonia. In CW, nitrogen removal ranges from 25 to 85% (U.S. EPA, 1988).

16.4.4. Phosphorus Removal

Phosphorus removal in wetlands is not very effective because of the limited contact opportunities between the wastewater and the soil. The principal mechanisms for phosphorus removal are plant uptake or retention in the soil (U.S. EPA, 1988).

If phosphorus removal is required, clay with iron and aluminum content should be considered. However, soils with a high phosphorus removal capacity are finer textured, and sand may be added to improve hydraulic conductivity. Also, iron or aluminum added to the substrate or fed into the wastewater can improve phosphorus removal (Steiner & Freeman, 1989).

16.4.5. Heavy Metals Removal

The predominant removal mechanisms in CW are precipitation and adsorption. Precipitation is enhanced by wetland metabolism which increases the pH of inflowing acidic waters to near neutrality. Removal of Cu, Zn and Cd at the rates of 99, 97 and 99%, respectively, for a residence time of 5.5 days in the Santee, CA, wetlands have been reported (U.S. EPA, 1988). However, metals removal will likely be finite due to exhaustion of the soil cation exchange capacity (CEC).

16.4.6. Trace Organics Removal

Municipal and industrial wastewaters contain variable concentrations of synthetic organic compounds. Adsorption of trace organics by the organic matter and clay particles present in the treatment system is thought to be the primary physicochemical mechanism for removal of refractory compounds in wetlands.

Other mechanisms can be biological degradation of easily degraded organic compounds, sedimentation and volatilization (U.S. EPA, 1988).

16.4.7. Pathogen Removal

The pathogens of concern in CW are parasites, bacteria and viruses. Pathogenic bacteria and viruses are removed by such mechanisms predation, sedimentation, absorption, and die-off from unfavorable environmental conditions, including UV in sunlight and temperatures unfavorable for cell reproduction (U.S. EPA, 1988). Table 3 reports performance data on pathogen removal for both FWS and SF wetlands in the US and Canada.

16.5. Design Equations

All CW systems can be considered to be attached growth biological reactors, and their performance can be described with first order plug-flow kinetics. Design equations given below for both FWS and SF systems should give a reasonable, and hopefully conservative, estimate of design requirements. However, a pilot test is strongly recommended for large-scale projects.

16.5.1. FWS Wetlands

BOD_5 removal in plug-flow reactors such as a wetland can be described by first-order model as follows (Reed et al., 1988):

$$\frac{C_e}{C_0} = \exp(-K_T t) \tag{1}$$

where C_e is the effluent BOD_5, mg/l; C_0, influent BOD_5, mg/l; K_T, temperature-dependent first-order reaction rate constant, $= k_{20}(1.06)^{T-20}\text{day}^{-1}$; t, hydraulic residence time, day (in calculating the t value, the wetland bed porosity and water loss by evapotranspiration (ET) must be taken into account); T, water temperature, °C; $k_{20} = 0.678\ \text{day}^{-1}$.

For an unrestricted flow system, hydraulic residence time can be expressed as:

$$t = \frac{LWd}{Q} \tag{2}$$

where L is the length of system, m; W, width of system, m; d, depth of system including the bed depth and water depth, m; Q, average flow rate $=$ $(Q_{\text{inf}} + Q_{\text{eff}})/2$.

Table 3: Pathogen removal in constructed wetland systems.

Location (vegetation)	**Winter season**			**Summer season**		
	Influent	**Effluent**[a]	**% Reduction**	**Influent**	**Effluent**[a]	**% Reduction**
Santee, CA (bulrush)[b]						
Total coli (no./100 ml)	5×10^7	1×10^5	99.80	6.5×10^7	3×10^5	99.54
Bacteriophage (PFU/ml)	1,900	15	99.21	2,300	26	98.87
Iselin, PA (cattails and grasses)[c]						
Fecal coli (no./100 ml)	1.7×10^6	6,200	99.64	1.0×10^6	723	99.93
Arcata, CA (bulrush)[d]						
Fecal coli (no./100 ml)	4,300	900	79.07	1,800	80	95.56
Listowel, Ont. (cattails)[d]						
Fecal coli (no./100 ml)	556,000	1,400	99.75	198,000	400	99.80

Modified from Reed et al. (1988).

[a] Undisinfected.

[b] Gravel bed, subsurface flow.

[c] Sand bed, subsurface flow.

[d] Free water surface.

In an FWS CW, because a portion of the available volume will be occupied by the bed media and the vegetation, the actual retention will be a function of the porosity (η), which can be defined as the remaining cross-sectional area available for flow:

$$\eta = \frac{V_V}{V} \tag{3}$$

where V_V and V are volume of voids and total volume, respectively.

The value of η for FWS CW is generally taken as 0.75. So the actual retention time is:

$$t = \frac{LWd\eta}{Q} \tag{4}$$

Reed et al. (1988) developed another general model for FWS CW design by combining the relationships in Eqs. (2) and (3) with Eq. (1):

$$\frac{C_e}{C_0} = A \exp\left[-\frac{0.7K_T(A_V)^{1.75}LWd\eta}{Q} \right] \tag{5}$$

where C_e is the effluent BOD_5, mg/l; C_0, influent BOD_5, mg/L; A, fraction of BOD_5 not removed as settleable solids near headworks of the system (as a decimal fraction); K_T, temperature-dependent rate constant, day^{-1}; A_V, specific surface area for microbial activity, m^2/m^3; L, length of system (parallel to flow path), m; W, width of system, m; d, design depth of system, m; η, porosity of system (as a decimal fraction); Q, average flow rate $= (Q_{inf} + Q_{eff})/2$.

The rate constant K_T (in day^{-1}) at water temperature T (in °C) and is defined by:

$$K_T = K_{20}(1.1)^{(T-20)} \tag{6}$$

where, K_{20} is the rate constant at 20°C.

Other coefficients in Eq. (5) have been estimated (Reed et al., 1988):

$$A = 0.52;\ K_{20} = 0.0057\ day^{-1};\ A_V = 15.7\ m^2/m^3;\ \eta = 0.75$$

When the bed slope or hydraulic gradient (S) is greater than 1%, it is necessary to adjust the design model accordingly:

$$\frac{C_e}{C_0} = A \exp\left[-\frac{0.7K_T(A_V)^{1.75}LWd\eta}{4.63S^{1/3}Q} \right] \tag{7}$$

Table 4 lists typical values used to test the equation against actual values at Listowel, Ontario, Canada. Table 5 summarizes design criteria for FWS wetlands. It should be noted in this table that an aspect ratio (L/W) of at least 10:1 is needed for FWS wetland systems to ensure plug-flow conditions and optimum treatment.

Table 4: Predicted vs. actual C_e/C_0 values for constructed wetlands at Listowel, Ontario.

Distance along channel (m)	Fall		Winter		Spring		Summer	
	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual
0	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
67	0.38	0.40	0.40	0.40	0.47	0.30	0.38	0.36
134	0.27	0.23	0.31	0.20	0.42	0.28	0.27	0.41
200	0.20	0.19	0.24	0.19	0.38	0.22	0.20	0.30
267	0.14	0.18	0.18	0.17	0.34	0.23	0.14	0.27
334 (final effluent)	0.10	0.15	0.14	0.17	0.30	0.26	0.10	0.17

Reed et al. (1988).

Table 5: Summary of design criteria for FWS constructed wetlands.

Organic loading (kg BOD_5/ha/day)	< 112
Actual retention time as determined by Eq. (5) or (7) (days)	3–15
Specific surface (A_V in Eq. (5) or (7)) for attached microbial growth (m^2/m^3)	15.7
Porosity (η value in Eq. (5) or (7)) of wetland flow path	0.75
Aspect ratio (L/W)	$\geq 10:1$
Water depth (cm)	
Warm months	<10
Cool months	<45

Reed et al. (1988).

Substituting these factors in Eq. (5) or (7) and rearranging terms to solve for retention time or for the required surface area produced the following equations for FWS wetlands.

Hydraulic residence time is given by:

$$t = \frac{(\ln C_0 - \ln C_e) - 0.6539}{65K_T} \tag{8}$$

If the bed slope or hydraulic gradient, is greater than 1%, then

$$t = \frac{(\ln C_0 - \ln C_e) - 0.6539}{301K_T S^{1/3}} \tag{9}$$

where, S is the bed slope in decimal fraction (e.g. for a 2% bed slope, S is equal to 0.02).

The design surface area of the wetland is given by

$$A = \frac{Q(\ln C_0 - \ln C_e - 0.6539)}{65K_T d} \tag{10}$$

If the bed slope or hydraulic gradient is greater than 1%

$$A = \frac{Q(\ln C_0 - \ln C_e - 0.6539)}{301K_T S^{1/3}} \tag{11}$$

Eqs. (8)–(11) are only valid for FWS wetlands meeting the conditions defined in the criteria summarized in Table 5. Design of wetlands with large unvegetated areas can use the general form presented in Eq. (5) or (7).

Example 1. Design an FWS wetland to produce advanced secondary effluent in a warm climate with a mean annual temperature of 25°C. The design flow is 760 m^3/day, influent wastewater is from a facultative lagoon with a BOD_5 concentration of 130 mg/l, and required effluent BOD_5 is 10 mg/l.

Solution

1. Assume the slope of the wetland bed will be 1% to allow drainage when required. Use Eq. (8) to estimate required retention time. At 25°C,

$$K_T = K_{20}(1.1)^{(T-20)} = 0.0057(1.1)^{(25-20)} = 0.0092\ \text{day}^{-1}$$

$$t = \frac{(\ln C_0 - \ln C_e) - 0.6539}{65K_T}$$

$$t = \frac{(\ln 130 - \ln 10) - 0.6539}{(65)(0.0092)} = 3.2\ \text{days}$$

2. For the warm climate site, use a 10-cm water depth on a year-round basis. If cattail plants are to be grown, the bed depth should be 30 cm, the total bed depth or d is 40 cm. Use Eq. (10) to estimate the surface area required.

$$A = \frac{Q(\ln C_0 - \ln C_e - 0.6539)}{65K_T d} = \frac{(760\ \text{m}^3/\text{day})(\ln 130 - \ln 10 - 0.6539)}{(65)(0.0092)(0.40\ \text{m})(10,000\ \text{m}^2/\text{ha})}$$

$$= 0.60\ \text{ha}$$

3. Use an aspect ratio (L/W) of 10:1 and determine the dimensions for the wetland channels, assuming a square plot is available.

$$A = LW = (10W)W = 600\ \text{m}^2$$

Thus $W = 7.75$ m, $L = 77.5$ m. Divide the square plot into 10 parallel channels, each 77.5 m long.

4. The design procedure assumes, and experience at operational systems confirms that SS and nitrogen concentrations in the effluent will also satisfy advanced secondary treatment requirements. Some of the remaining nitrogen will be in the ammonia form. If stringent ammonia limits prevail, recycle of wetland effluent should be incorporated in the system design. The amount of recycle required will depend on the ET losses for the area and should be sufficient to maintain the 3.2-day retention time.

16.5.2. SF Wetlands

The major oxygen source for the subsurface components (soil, gravel, rock, and other media in trenches or beds) is the oxygen transmitted by the vegetation to the root zone. In most cases, the SF system is designed to maintain flow below the surface of the bed, so there can be very little direct atmospheric reaeration.

The selection of plant species is therefore an important factor. The root penetration of the various plants (see Table 1) makes it possible to remove BOD_5 in the expanded aerobic zone.

Root penetration is important for the oxygen transfer and treatment of organics and nitrogen at the full bed depth. The maximum treatment potential, and possibly the maximum design hydraulic loading, may not be realized until the roots and rhizomes have penetrated to their full potential depth. Reed et al. (1988) recommended that the depth of root penetration, as listed in Table 1, be used as the design depth for SF systems.

BOD_5 removal in SF systems can be described with first-order kinetics, as described in Eq. (1) for FWS systems. Eq. (1) can be rearranged and used to estimate the required surface area for an SF system. Both forms of the equation are shown below for convenience.

$$\frac{C_\mathrm{e}}{C_0} = \exp(-K_\mathrm{T}t) \tag{1}$$

$$A_\mathrm{s} = \frac{Q(\ln C_0 - \ln C_\mathrm{e})}{K_\mathrm{T}d\eta} \tag{12}$$

where C_e is the effluent BOD_5, mg/l; C_0, influent BOD_5, mg/l; K_T, temperature-dependent first-order reaction rate constant, $= k_{20}(1.06)^{T-20}$ day^{-1}; t, hydraulic residence time, day; Q, average flow rate through the system, m^3/day; d, depth of submergence, m; η, porosity of the bed, as a fraction; A_s, surface area of the system, m^2.

The saturated cross-sectional area for flow through an SF system can be calculated according to Darcy's law:

$$A_\mathrm{c} = \frac{Q}{k_\mathrm{s}S} \tag{13}$$

where A_c is the $d{\cdot}W$, cross-sectional area of wetland bed, perpendicular to the flow direction, m^2; d, bed depth, m; W, bed width, m; k_s, hydraulic conductivity of the medium, $\mathrm{m}^3/\mathrm{m}^2$ day; S, slope of the bed, or hydraulic gradient (as a decimal fraction).

Bed cross-sectional area and bed width are independent of temperature (climate) and organic loading since they are controlled by the hydraulic characteristics of the media.

The value of K_T can be calculated from suggested k_{20} values for SF CW systems (Table 6). Table 6 lists expected porosities (η), hydraulic conductivity and k_{20}.

To avoid disruption of the medium-rhizome structure and to ensure sufficient contact time for treatment, the unit flow velocity (Q/A_c), which is equal to $k_\mathrm{s}S$ according to Eq. (13) through a cross-section of the medium should not exceed 8.6 m/day (Reed et al., 1988).

Table 6: Media characteristics for subsurface flow systems.

Media type	**Maximum 10% grain size (mm)**	**Porosity (η)**	**Hydraulic conductivity (k_s) (m^3/m^2/day)**	k_{20}
Medium sand	1	0.42	420	1.84
Coarse sand	2	0.39	480	1.35
Gravelly sand	8	0.35	500	0.86

U.S. EPA (1988).

Example 2. Design an SF wetland to produce advanced secondary effluent in a warm climate with a mean annual temperature of 25°C. The design flow is 760 m^3/day, influent wastewater is from a facultative lagoon with a BOD$_5$ concentration of 130 mg/l, and required effluent BOD$_5$ is 10 mg/l. (*Note*: These are the same conditions used in Example 1, so comparisons can be made.) The predominant wetland plant type in surrounding marshes is cattail.

Solution

1. Choose cattail for this SF system since it is successfully growing in local wetlands. From Table 1, cattail rhizomes penetrate about 30 cm into the medium. So the bed media depth (d) should be 30 cm.
2. Choose a slope of 1% ($S = 0.01$) for ease of construction.
3. Choose a gravelly sand as the medium. From Table 6, $k_s = 500\ \mathrm{m}^3/\mathrm{m}^2$ day. Check the suitability of a 1% slope.

$$k_s S = (500\ \mathrm{m}^3/\mathrm{m}^2\ \mathrm{day})(0.01) = 5.0\ \mathrm{m/day} < 8.60\ \mathrm{m/day}$$

4. From Table 6, $k_{20} = 0.86$. Solve for K_T using Eq. (12).

$$K_T = k_{20}(1.06)^{(T-20)} = 0.86(1.06)^{(25-20)} = 1.34\ \mathrm{day}^{-1}$$

5. Determine the cross-sectional area of the bed using Eq. (13).

$$A_c = Q/(k_s S) = 760/5.0 = 152\ \mathrm{m}^2$$

6. Determine the bed width.

$$W = A_c/d = 152/0.3 = 507\ \mathrm{m}$$

7. Determine the surface area required using Eq. (12).

$$A = \frac{Q(\ln C_0 - \ln C_e)}{K_T d\eta} = \frac{(760\ \mathrm{m}^3/\mathrm{day})(\ln 130 - \ln 10)}{(1.34)(0.3)(0.35)}$$

$= 13,854\ \mathrm{m}^2$, requiring more area than FWS constructed wetlands due to

× low porosity.

8. Determine the bed length (L) and the retention time (t) in the system.

$$L = A_s/W = 13,854/507 = 27.3\ \mathrm{m}$$

$$t = LWd\eta/Q = (27.3)(507)(0.3)(0.35)/(760) = 1.91\ \mathrm{days}$$

16.6. Other Considerations

16.6.1. Hydraulic Budget

For a CW, the water balance can be expressed as follows:

$$Q_i - Q_0 + P - \mathrm{ET} = \frac{\mathrm{d}V}{\mathrm{d}t} \tag{14}$$

where Q_i is the influent wastewater flow, volume/time; Q_0, effluent wastewater flow, volume/time; P, precipitation, volume/time; ET, evapotranspiration, volume/time; V, volume of water; t, time.

Groundwater inflow and infiltration are excluded from Eq. (14) because of the impermeable barrier. If the system operates at a relatively constant water depth ($\mathrm{d}V/\mathrm{d}t = 0$), the effluent flow rate can be estimated using Eq. (14). Historical climatic records can be used to estimate precipitation and ET.

16.6.2. Site Selection

A CW can be constructed almost anywhere. Because grading and excavating represent a major cost factor, topography is an important consideration in the selection of an appropriate site. In selecting a site for an FWS wetland, the most desirable soil permeability is 10^{-6}–10^{-7} m/sec. Sandy clays and silty clay loams can be suitable when compacted. In heavy soils, additions of peat moss or top soil will improve soil permeability and accelerate initial plant growth.

16.6.3. Flow Patterns

A CW cell is designed to use one or more of three types of flow patterns: plug flow, step feed, or recirculation. Plug flow (Fig. 3a) is once-through flow down the cell length. Plug flow is now used for most municipal and acid drainage systems and requires minimal piping, energy use, operation, and maintenance.

Step feed (Fig. 3b) may benefit pollutant removal by using more of the CW area for solids removal and by providing carbon for nitrogen removal in the lower bed area. Step feed is typically combined with recirculation. The cost–benefit of step feed needs investigation.

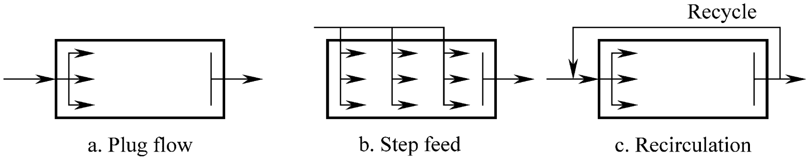
Recirculation (Fig. 3c) should be considered, and its potential needs further investigation. Recycling treated effluent will dilute influent BOD_5 and SS, decreasing odor potential and increasing dissolved oxygen concentration and retention time, which will enhance nitrification and subsequent nitrogen removal (Steiner & Freeman, 1989).

16.6.4. Slope

A slope of 0.5% or less, as limited by construction tolerances, is recommended for an FWS system. Some slope is needed to drain the cell for maintenance and possible mosquito control. SF bed slopes should be 2% or less based on the initial hydraulic conductivity of the substrate. A level substrate surface is recommended for an SF system to facilitate vegetation planting and to control weed by flooding the bed. Bed slopes greater than 4% would cause most of the flow to be on the surface due to poor hydraulic conductivity, with channeling, treatment, and vegetation management problems (Steiner & Freeman, 1989).

16.6.5. Liners

If groundwater contamination or water conservation is a concern, an impermeable liner below the substrate is required. Possible materials are compacted in situ soil



a. Plug flow b. Step feed c. Recirculation

Figure 3: Flow patterns for constructed wetlands.

(permeability less than 10^{-6} cm/sec); bentonite; asphalt; synthetic butyl rubber; or plastic membranes. The liner must be strong, thick, and smooth to prevent root penetration and attachment (Steiner & Freeman, 1989).

16.7. Operation and Maintenance

Two operational considerations associated with wetlands for wastewater treatment are mosquito control and plant harvesting. In addition, system disturbances can occur from time to time.

16.7.1. Mosquito Control

Mosquito problems may occur when wetland treatment systems are overloaded organically and anaerobic. Strategies used to control mosquito populations include effective pretreatment to reduce total organic loading; step feeding of the influent wastewater stream with effective influent distribution and effluent recycle; vegetation management; natural controls, principally by mosquito fish (*Gambusia affinis*), in conjunction with the above techniques; and application of man-made control agents. In general, natural controls are preferred because of a concern that man-made control agents resistant might develop resistant strains of mosquito (Wieder et al., 1989).

16.7.2. Plant Harvesting

The usefulness of plant harvesting in wetland treatment systems depends on several factors, including climate, plant species, and the specific wastewater objectives. Harvesting plants to remove wastewater contaminants taken up by the plants is inefficient. However, plant harvesting can affect treatment performance of wetlands by altering the effect that plants have on the aquatic environment. Further, because harvesting reduces congestion at the water surface, control of mosquito larvae using fish is enhanced. Where a segmented wetland system is used, drying each segment separately allows harvesting with conventional equipment. Depending on location, burning the dried plant mass in place may be most economical (Wieder et al., 1989).

16.7.3. System Perturbations and Operation Modifications

Deviations from “average” operating conditions will occur in the system lifetime with greater frequency than predicted or preferred. Perturbations generally are of two types (Girt & Knight, 1989): (1) predictable perturbations, which can be predicted and occur periodically; and (2) unpredictable perturbations, which are unforeseen in the design phase or which occur so infrequently that incorporation into the design would entail unnecessary expense. Tables 7 and 8 summarize, respectively, predictable and unpredictable events, along with operational features most affected, associated symptoms, and appropriate operation modifications.

16.8. Case Studies

16.8.1. Case Study A: Emmitsburg, Maryland, USA, SF Constructed Wetland

The town of Emmitsburg constructed an SF system with a design flow rate of 130 m^3/day in 1984 to treat a portion of its effluent flow. The system is a single basin, 76.3 m long, 9.2 m wide, and 0.9 m deep, filled with 0.6 m of crushed rock. Clay was used in the bottom of the basin to prevent groundwater contamination. Perforated pipes placed near the bottom of the basin are used for influent distribution and effluent collection. The water level during normal operation is approximately 5 cm below the surface of the gravel. The system was initially seeded with 200 broadleaf cattail plants in August 1984 and another 200 in July 1995. By March 1986, about 35% of the basin surface area was covered by cattails. The planting density used should have been at least an order of magnitude higher. Until the plants cover the entire basin, the performance will not be representative of an SF system.

The influent to the Emmitsburg system is trickling filter effluent. Influent flows vary between 95 and 132 m^3/day, which corresponds to a surface hydraulic loading rate of 1,420–1,870 m^3/ha/day. Effluent samples are collected and analyzed weekly for BOD_5, SS, TDS, DO and pH.

The influent BOD_5 concentrations to the system range between 10 and 180 mg/l while SS concentrations normally range between 10 and 60 mg/l. Results from two years of operation are presented in Table 9, which show very good performance even with the limited plant coverage. Odors in the effluent have been an occasional problem but the frequency of noticeable odors is decreasing as cattail coverage increases. The engineering and construction costs of the Emmitsburg system were less than US$35,000.

16.8.2. Case Study B: The Eastern Seaboard Industrial Estate (ESIE), Rayong Provice, Eastern Thailand, Vertical-Flow Constructed Wetlands

The ESIE comprises of over 100 industrial factories and 14,000 staff. The industries are required to pre-treat their wastewaters to remove heavy metals

Table 7: Predictable system disturbances.

Disturbance	Features	Symptoms	Operation modifications
Startup	Difficulties in vegetation establishment and microbial flora colonization	Widely fluctuating treatment efficiencies	Control loading rates, i.e. water flow rate, chemical concentration water inflow rates freshwater source Control water depths — critical for vegetation establishment and development of conditions suitable for target microbial populations Dilution/recirculation Chemical additions (e.g. lime to improve soil pH, fertilizer)
Seasonal	Extreme precipitation	High loading rates	Control loading rates, i.e. water flow rates, chemical concentration Water inflow rates Dilution Recirculation
		Decreased storage capacity	Increase storage capacity Stormwater diversion Detention pond Increase water depth
		Insufficient residence times;	Control outflow rates
		Channeling	Install baffles
	Extreme low temperatures	Insufficient flow	Freshwater source, recirculation, parallel cells
		Freezing; sheet flow over ice surface	Recirculation, aeration, control water depth Preheated water

(*continued*)

Table 7: Continued.

Disturbance	Features	Symptoms	Operation modifications
	Vegetation growth/decay	Flushing of chemicals, nutrients, and microbes from decaying vegetation, sediment	Secondary treatment pond
			Vegetation harvest or burning Recirculation to increase nutrient retention
	Population composition changes (microbial, algal)	Gradual change in treatment efficiency	Secondary treatment pond
			Recirculation

Girt and Knight (1989).

and other toxic compounds according to the Thailand effluent standards prior to discharging into combined sewers and mixing with other domestic wastewaters. The current wastewater flow rate (year 2000) is about 7,000 m^3/day.

This combined wastewater is being treated by two CW in series, each with a dimension of $35 \times 18 \times 0.8$ m^3 (length × width × depth). The CW beds are lined with high-density polyethylene sheet and filled with 1-cm gravel. Wastewater is applied intermittently over the CW beds in a vertical-flow mode, and the percolates are collected through underdrainage pipes. Cattails, bulrushes and canna are the primary vegetation grown in these CW beds.

During the period of September 2001–May 2002, these CW units were operated at the following conditions: hydraulic loading rates 60–160 l/m^2/day; organic loading rate 57–140 kg BOD_5/ha/day and hydraulic retention times 1.4–4.0 days. The treatment performance of these CW units in series was found satisfactory (Table 10) with the effluent BOD_5 and SS concentrations being 4 and 10 mg/l, respectively. Because of the nitrification reactions occurring in the CW beds, there was an increase in NO_3-N concentration from 0.06 mg/l in the effluent to 4.75 mg/l in the effluent. This treated water is being sold to some factories located in the ESIE for uses in factory air-cooling and other processes.

Due to prolific growth of the vegetation under tropical conditions, plant harvesting was done once in 4 months, with annual yields of 130–150 t/ha/yr (wet

Table 8: Unpredictable system disturbances.

Disturbance	**Symptoms**	**Operation modifications**									
		Water inflow	**Water outflow**	**Water depth**	**Dilution**	**Recirculation**	**Pretreatment pond**	**Chemical addition**	**Vegetation harvest**	**Replant**	**Predator control**
Record storm event	High hydraulic loading rates	x				x	x				
	Decreased storage capacity	x					x				
	Insufficient residence time	x	x	x	x	x	x	x			
	Channeling	x					x				
	High sediment loads			x			x				
	High chemical loads		x		x	x	x	x			
Change in chemical constituents and concentrations	High chemical loads	x			x		x	x			
	Increased toxicity (vegetation, wildlife)				x			x	x	x	
	Release of chemicals from Sediments/vegetation		x	x		x			x	x	
	Change in chemical form			x	x						

(*continued*)

Table 8: Continued.

Disturbance	**Symptoms**	**Operation modifications**									
		Water inflow	**Water outflow**	**Water depth**	**Dilution**	**Recirculation**	**Pretreatment pond**	**Chemical addition**	**Vegetation harvest**	**Replant**	**Predator control**
Vegetation damage	Increased debris, flow hindrance	x		x					x	x	
	Nutrient release from vegetation		x	x					x	x	
	Change in conditions for replanting	x		x		x	x		x	x[a]	
	Complaints from neighbors			x				x			x
Pests (rodents, mosquitoes, etc.)	Reduced flow and water level control	x	x	x	x	x	x	x			
	Inability to respond to need for changes in operations[b]										
Malfunctions/ construction failures	Limited treatment capacity[b]										
	Limited lifespan[b]										
Design flaw											

Girt and Knight (1989).

[a] New species.

[b] All operation modifications may need to be considered.

Table 9: Performance of the Emmitsburg SF system.

Season	**Average flow (m^3/day)**	**BOD_5 (mg/l)**		**SS (mg/l)**		**Effluent DO (mg/l)**	**Area covered with cattails (%)**
		Inf.	**Eff.**	**Inf.**	**Eff.**		
Fall 1984	117	29	12	25	7	1.0	<5
Winter 1985	111	68	29	37	9	0.3	<10
Spring 1985	130	117	38	37	13	0.0	<20
Summer 1985	100	87	11	28	10	1.3	<25
Fall 1985	97	28	7	29	7	2.1	<30
Winter 1986	106	40	11	25	4	–	<35

U.S. EPA (1988).

weight). These harvested plants can be used in making furniture and other decorations, another income generation for the ESIE.

16.8.3. Case Study C: Vertical-Flow Constructed Wetlands for Septage Dewatering and Stabilization, Asian Institute of Technology (AIT), Bangkok, Thailand

Septic tank sludge (or septage) usually contains high solid, organic and enteric microorganism contents, with poor setting and dewatering characteristics. A pilot

Table 10: Treatment performance of the CW unit.

Parameter	**Average concentration (mg/l)**			**Overall removal (%)**
	Influent	**Effluent unit 1**[a]	**Effluent unit 2**[b]	
BOD	88	19	4	95.8
COD	229	52	19	91.5
SS	98	16	10	89.5
TKN	24.1	14.5	4.6	81.1
NH_3-N	14.2	10.8	3.3	76.7
NO_3-N	0.06	0.53	4.75	–[c]
TP	7.0	4.7	1.5	78.5

AIT (2002).
[a] Percolate of CW unit 1.
[b] Percolate of CW unit 2 in series.
[c] Increased likely due to nitrification reaction.

study was carried out at the AIT campus during 1998–2001 to demonstrate the feasibility of applying vertical-flow CW to dewater and stabilize septage collected from Bangkok city, Thailand.

Three pilot-scale CW beds, each with a surface area of 25 m^2, having 65 cm sand–gravel substrata, supported by a ventilated drainage system (Fig. 4) were planted with narrow-leave cattails (*Typha augustifolia*). To operate in a vertical-flow mode, the Bangkok septage (Table 11) was uniformly distributed on the CW beds 1–2 times weekly at the solids loading rate (SLR) of 1.5–9.6 kg TS/m^2 week, while the percolate was collected from the drainage system for further treatment.

The experimental data obtained so far indicated the SLR of 4.8 kg TS/m^2 week to be the most suitable, resulting in the highest TS, COD and TKN removal of 80, 96 and 92%, respectively (Koottatep et al., 2001). The TS contents of the dewatered septage remaining on the CW beds were increased from 1–2 to 30–60% with the one-week operation cycle. Because of the vertical-flow mode of operation and with the effectiveness of the ventilation pipes, there was a high degree of nitrification occurring in the CW beds — the NO_3-N contents were found to increase from about 4 mg/l (in the Bangkok septage) to 180–250 mg/l in the CW percolate.

Due to rapid flow-through of the percolates, there was little liquid retained in the CW beds, causing the cattail plants to wilt, especially during the dry season. To reduce the wilting effects, the operating strategies in the second year were modified by ponding the percolate in the CW beds for periods of 2 and 6 days prior to discharge. This operating strategy was found beneficial not only for mitigating plant wilting, but also for increasing N removal through enhanced denitrification activities in the CW beds. During the 3-year operations, the dewatered septage was

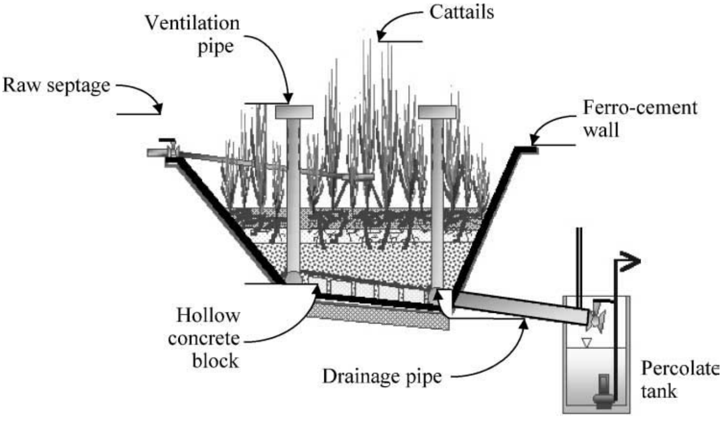


Figure 4: Schematic diagram of pilot-scale CW units.

Table 11: Characteristics of Bangkok septage samples.

Parameter	Range	Average	Standard deviation
pH	6.7–8.0	7.5	0.6
TS (mg/l)	2,200–67,200	19,000	12,500
TVS (mg/l)	900–52,500	13,500	9,400
SS (mg/l)	1,000–44,000	15,000	10,100
BOD (mg/l)	600–5,500	2,800	1,400
TCOD (mg/l)	1,200–76,000	17,000	15,000
TKN (mg/l)	300–5,000	1,000	800
NH_4 (mg/l)	120–1,200	350	170
NO_3 (mg/l)	1–11	4.5	3.5
Helminth eggs (no./g of sample)	0–14	4	1

Based on 120 raw septage samples during August 1997–February 1999.

not removed from the CW beds and no adverse effects on the septage dewatering efficiency were observed.

As can be expected, the dewatered spetage, after 2–3 years of decomposition in the CW beds, was a well-stabilized sludge without the presence of viable helminth eggs, suitable to be used as a fertilizer or soil conditioner.

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