of the four

Additional area is required for storage and a buffer zone around the site.

19.7 WETLANDS FOR WASTEWATER TREATMENT

Wetlands are natural wet ecosystems with diverse and complex roles in nature. Definitions of wetlands vary (Mitsch and Gosselink, 1993) but fundamentally all wetlands are at least intermittently flooded with water. Although historically many cultures lived in harmony with wetlands, modern society has until recently regarded wetlands as nuisances to be drained for development; thus, they have disappeared at a high rate in North America. A variety of wildlife from fish to waterfowl is found in wetlands and dependent on them for survival. Peat, foods, and timber may be harvested from wetlands. They are an important sink for nutrients or other substances and perform other ecological functions besides being aesthetic. Over the past 30 yr the importance of wetlands has been recognized and formalized into government support programs and legislation for wetlands preservation and reestablishment of wetlands beyond the traditional support of conservation groups and other interested parties. Wastewater is an amenity to establish and support wetlands.

Although the definition of wetlands systems varies, estimates of wetlands area in Canada are 14% of Canada or 127 million ha (Zoltai, 1988). Dahl and Johnson (1991) estimate the wetland area in the conterminous United States at 41.8 million ha (103 million acres). The Government of Canada has adopted a policy that includes goals of preventing net loss of wetlands, enhancement and rehabilitation of wetlands in critical areas, and recognition of wetlands functions in resource planning (Government of Canada, 1991). Similarly the U.S. Government supports a variety of wetland protection programs. Increased emphasis on wastewater treatment and government wetlands support programs converged near the mid-1980s, resulting in a significant rise in the number of wetlands systems designed for wastewater treatment with a concomitant rise in study of these systems.

Natural wetlands throughout the world are populated by emergent vegetation. Cattail (*Typha* spp.), reed (*Phragmites* spp.), sedges (*Carex* spp.), bulrushes (*Scirpus* spp.), rushes (*Juncus* spp.), and grasses are the more familiar species (Mitsch and Gosselink, 1992; USEPA, 1988). Floating aquatic plants most extensively used in wastewater treatment systems are the water hyacinth (*Eichhornia crassipes*) and duckweeds (*Lemna* spp.). Vegetation in natural wetlands is a function of the type of wetlands and its location. Mitsch and Gosselink (1993) provide a more extensive list of plant species that are found naturally and have been planted in constructed wetlands.

Wetlands are designed to remove conventional pollutants of BOD, SS, and nutrients. Heavy metals can also be removed to a significant extent. Settled sewage, effluent from secondary treatment, stormwater runoff, leachate, acid mine wastes, and industrial wastewaters have been treated in wetlands; the most common application of wetlands is for polishing secondary effluent. Removal of BOD, SS, N, P, and heavy metals from secondary effluent does not occur to a greater extent in wetlands than in other forms of land treatment (Richardson and Nichols, 1985).

When water is present, anaerobic conditions develop in the upper layers of the soil that influence the biology and chemistry functions of wetlands systems. Plants must be able to survive in anoxic or anaerobic soil conditions over extended periods of time. Denitrification, which is important for wastewater treatment, and swamp gas (methane) production are some consequences of anaerobic conditions. The capability of wetlands to remove nitrogen through denitrification is well established.

The accumulation of nutrients and organics in a wetlands follows from growth of vegetation, death or dieback, decay, and finally soil accretion. The times for 50% of a plant to dieback and fall to the ground (half-life) were surveyed by Kadlec (1989a) for a number of common plants found in wetlands. Half-lives of above ground plants ranged from 220 to 850 d; roots and woods half-lives vary from 14 to 70 yr. From analysis of plant growth and decay times, Kadlec (1989a) concluded that probable startup times for wetlands are 5–10 yr and that data available are overly optimistic since the wetlands are still in a saturation phase.

Biomass typically contains 2 and 0.4% nitrogen and phosphorus, respectively. Once stationary conditions have been reached only biomass accumulation results in removal of nutrients. Kadlec (1989a) calculated that a wetland with 10-d detention time, hydraulic loading rate of 200 m^3/ha/d (21 400 gal/acre/d), and influent nitrogen and phosphorus concentrations of 10 mg/L would only remove 1.4 and 0.7% of the applied nitrogen and phosphorus, respectively, with a soil accumulation rate of 2.5 mm/yr (0.1 in./yr) with soil having the same nutrient content as living biomass. This soil accumulation rate was observed for a natural wetland 800 years old, but wetlands receiving wastewater may exhibit significantly different rates.

Mitsch and Gosselink (1993) note that there is no consensus on whether wetlands serve as net sources or sinks for nitrogen and phosphorus. Extensive data acquisition is required over long periods of time to establish average mass balances in the complex, dynamic environment of a wetland. They note with caution that freshwater marshes have been more often evaluated as sinks for nitrogen and phosphorus, particularly when sewage is applied to the wetlands. There are many contradictory studies and phosphorus is among the least predictable elements.

Harvesting vegetation is generally not practical because of the labor involved and the small portion of nutrients that may be removed by harvesting (USEPA, 1988). In one operation, weed eaters, machetes, and rakes were used for manual harvesting. Harvesting rates were approximately 181 m^2/person/d (1 950 ft^2/person/d) (Gearhart et al., 1989). Harvested cells had slightly higher effluent SS concentrations than unharvested cells; BOD removal was not affected by harvesting. A survey of the literature by Guntenspergen et al. (1989) showed that emergent vegetation only incorporated a small percentage of added nutrients into biomass, with the exception of water hyacinths and other free floating wetland plants, which sequester significant amounts of nutrients and heavy metals.

Constructed wetlands for wastewater treatment at Listowel, ON. Courtesy of Gore & Storrie Limited.

Two types of wetlands systems are designed. Surface flow systems are similar to natural wetlands and a free water surface is maintained. The other alternative is a subsurface flow system (Fig. 19.3) where the water flows through a permeable medium. Emergent vegetation is supported in these systems. Treatment is generally better in subsurface flow systems and these systems do not have mosquito problems.

The water budget for a wetlands is described by the following equation:

$$P - A + Q_i + G_i - Q_o - G_o - \mathrm{ET} = \frac{dV}{dt} \tag{19.31}$$

where

P is precipitation
A is abstractions from precipitation
Q_i is surface inflow
G_i is groundwater inflow
Q_o is surface outflow
G_o is groundwater outflow
ET is evapotranspiration
V is volume of water storage in the wetlands
t is time

A comprehensive design of a wetlands system would consider variation in all of these variables over a long-term period to ensure that minimum water depths are maintained during periods of drought and that detention times are sufficient during wet years. All terms must be considered when sewage is applied to natural wetlands. Constructed wetlands are usually designed with compacted soil where suitable or an impermeable liner to prevent groundwater contamination (Reed et al., 1988; USEPA, 1988). Organic soil layers in natural wetlands reduce infiltration rates to very low values. Stormwater runoff is normally diverted from wetlands for wastewater treatment. Field measurements are required to establish parameters used in the water balance equation.

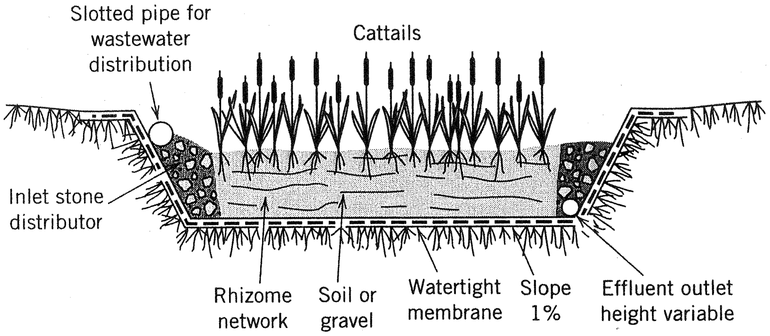

Figure 19.3 Subsurface flow wetlands system. After USEPA (1988).

Kadlec (1989b) describes some of the techniques used and gives equations for terms in the water balance equation.

Commonly a simpler approach is used for wetlands design. Hydraulic loading rate is the primary control variable for wetland systems. Variable recommendations exist in the literature. Based on a database of 44 surface flow constructed wetlands receiving effluent from biological treatment plants, hydraulic loadings of 500 m^3/ha/d (53 500 gal/acre/d) or less will achieve effective reductions (>60%) of BOD and TSS (Knight, 1993). Performance data for a number of systems are listed in Watson et al. (1989) and WPCF (1990). From these data it appears that subsurface systems can be loaded at higher surface loading rates compared to surface systems and achieve the same removals. Performance data comparisons must consider differences in operating conditions among systems. Some systems receive high concentrations of BOD and SS from only screened or settled wastewater and removals tend to be higher. A system receiving 20 mg/L of BOD_5 would only remove 75% of the BOD_5 if the effluent concentration were 5 mg/L. Effluent concentrations at lower values would be difficult to achieve. Preliminary design guidelines listed in Table 19.11 were suggested by Watson et al. (1989).

Loadings must be reduced to 100–150 m^3/ha/d (10 700–16 000 gal/acre/d) or less to achieve nitrification and nutrient removal of 60% or more. Richardson and Nichols (1985) suggested typical hydraulic loadings of 10–40 m^3/ha/d (1 050–4 300 gal/acre/d) to achieve greater than 50% removal of N and P. Using per capita loading rates of

TABLE 19.11 Suggested Hydraulic Loading Rates of Wetlands[a]

	Hydraulic loading, m^3/ha/d (gal/acre/d)	
Treatment	Surface flow	Subsurface flow
Basic treatment	[b]	230–620 (24 600–66 300)
Secondary treatment	120–470 (12 800–50 200)	470–1 870 (50 200–200 000)
Polishing treatment	190–940 (20 300–100 500)	470–1 870 (50 200–200 000)

[a] Reprinted with permission from J. T. Watson, S. C. Reed, R. H. Kadlec, R. L. Knight, and A. E. Whitehouse (1989), "Performance Expectations and Loading Rates for Constructed Wetlands," in *Constructed Wetlands for Wastewater Treatment,* D. A. Hammer, ed., Chelsea, MI. Copyright 1989 Lewis Publishers, an imprint of CRC Press, Boca Raton, FL.

[b] Insufficient data.

2.2 g P/d and 10.8 g N/d, Nichols (1983) estimated that 1 ha (2.5 acres) of wetland would remove 50% of these nutrients for 60 people. Area requirements would increase to 1 ha for 20 persons to achieve 75% removals. These estimates were based on performance of 9 wetlands systems receiving secondary effluent; the wetlands had been in operation for 3–69 years.

Depths in surface flow wetlands are usually less than 0.5 m (1.6 ft) (WPCF, 1990). As depths increase to 0.7–1.0 m (2.3–3.3 ft), floating plants replace emergent vegetation. At a depth of 0.5 m (1.6 ft) and hydraulic loading rate of 500 m^3/ha/d (53 500 gal/acre/d) the nominal detention time in a wetlands would be 10 d. The actual detention time would be less than this because of the volume occupied by vegetation. Many sources agree that the minimum detention time should be around 5 d, particularly if high nitrogen removals are desired.

A PF first-order removal expression is commonly used as the basic performance model in surface flow wetlands.

$$C = C_0 e^{-kAD/Q} \tag{19.32}$$

where

C and C_0 are the effluent and influent BOD$_5$ concentrations, respectively
D is depth of submergence of the bed
A is the surface area of the bed
Q is the influent flow rate

Different variations of this model have been reported by Reed et al. (1988) and Kadlec (1989b) and all models incorporate some empirical coefficients. These models and other equations below have not been tested extensively; more study will be required. Constructed wetlands are often configured as a series of cells. Flow through a series of cells with vegetation will be close to a PF regime. Single-cell and more open configurations will exhibit variable flow.

The rate constant is subject to temperature. In northern climates ice cover will not prevent water movement under the ice but treatment efficiency is reduced and some storage must be provided (Kadlec, 1989b). Performances reported above are for nonfreezing conditions. Pilot plant studies are required to determine the rate constant variation in different seasons.

There is much more agreement on the equations used to design subsurface flow systems (Cooper and Hobson, 1989; Reed et al., 1988; Watson et al., 1989). Flow through subsurface systems will be PF and Eq. (19.32) is applied. Reed et al. (1988) propose a relationship for k that they note is only tentative:

$$k_{20} = k_0(37.31e^{4.172}) \tag{19.33}$$

where

k_0 is the optimum rate constant for a medium with a fully developed root zone; 1.839 d^{-1} for typical municipal wastewater, 0.198 d^{-1} for industrial wastewater with high COD
k_{20} is the rate constant at 20°C, d^{-1}
e is total porosity of the medium

Typical values of porosity for sand are given in Table 14.3. Porosity will vary from 0.18 to 0.35 for coarse to fine gravel (Reed et al., 1988). Equation (19.5) is used to describe the temperature variation of k; θ has a value of 1.1.

Europeans have much more experience with subsurface flow systems. For Q in m^3/d and A in m^2, k in Eq. (19.32) is taken in the range of 7–12 d^{-1} according to the typical designs in the United Kingdom for reed bed systems (Cooper and Hobson, 1989). The design strength of domestic sewage in the United Kingdom is 330 mg BOD_5/L.

The cross-sectional area of a bed is calculated from Darcy's law:

$$Q = KA_c \frac{\Delta h}{\Delta L} \tag{19.34}$$

where

K is the hydraulic conductivity of the fully developed bed in m/s
A_c is the cross-sectional area of the bed in m^2
$\Delta h / \Delta L$ is the slope of the bed

In a shallow, saturated bed the hydraulic gradient and the slope will practically be the same. Reed et al. (1988) suggest that 0.001 or a lower value should be used for $\Delta h / \Delta L$ when the bed is flat and the gradient is controlled with an overflow weir.

Cooper and Hobson (1989) note that using hydraulic conductivities less than 10^{-4} m/s (3.9×10^{-3} in./s) results in short, unacceptably wide beds and most United Kingdom beds have been designed using values between 10^{-4} and 3×10^{-4} m/s (3.9×10^{-3}–0.12 in./s) but these values will also tend to result in wide beds. These values are higher than conductivities experienced in typical systems and some overland flow is expected. If a gravel medium is used, conductivities may reach 10^{-3} m/s (0.039 in./s). The typical depth of beds is 0.6 m (2 ft) because root systems tend to weaken below this depth and to prevent beds from freezing. Slopes depend on the hydraulic conductivity but values up to 4–5% or higher may be used. In young reed beds generally receiving screened domestic sewage and monitored over a 2-yr period, BOD and SS performance was good with BOD removals of 65% or better and SS removals generally above 65%. Nitrogen and phosphorus removals were low to negligible.

There are only two published quantitative design criteria for wetlands for acid mine drainage (Wieder et al., 1989). The U.S. Bureau of Mines from a survey proposed the empirical design rule of 4.9 m^2 for each L/min of flow (200 ft^2 per gal/min) (Girts and Kleinmann, 1986). The survey excluded sites where outflow metals exceeded inflow metals. The guideline was developed for flows of 19–38 L/min (5–10 gal/min), pH above 4.0, and Fe and Mn concentrations less than 50 and 20 mg/L, respectively. The Tennessee Valley Authority (TVA) developed the following empirical design criteria to achieve effluent Fe and Mn concentrations less than 3 and 2 mg/L, respectively (Brodie et al., 1988).

For Fe:
pH <5.5, 2 m^2 (22 ft^2) is required per mg Fe/min in the influent
pH >5.5, 0.75 m^2 (8 ft^2) is required per mg Fe/min in the influent

For Mn:
pH <5.5, 7 m^2 (75 ft^2) is required per mg Mn/min in the influent
pH >5.5, 2 m^2 (22 ft^2) is required per mg Mn/min in the influent

Mosquito control is an important issue associated with wetlands. Measures recommended for mosquito control include keeping BOD loading rates under 110 kg/ha/d (98 lb/acre/d) to avoid stagnant zones where anaerobic conditions may occur. Natural predators of mosquito larvae such as dragonflies and water beetles require aerobic conditions. Uniform distribution or application of the influent throughout the wetlands should be practiced (Stowell et al., 1985). Control measures are not well understood.

Weed growth can be a problem; weeds can shade the more desirable species and retard their growth. In subsurface flow systems weeds were best controlled by flooding the bed (Cooper and Hobson, 1989). A level surface enhances flooding of the bed.

Pathogen Removal in Wetlands

In studies on surface flow and subsurface flow wetlands in California, Gersberg et al. (1989) found bacterial and viral indicators to be removed in the range of 90–99%. From their review of the literature they concluded that constructed wetlands could reduce total coliforms to 10^3/100 mL or lower if secondary wastewaters were being treated. Raw or primary wastewaters would not experience removals to this level in wetlands without disinfection.

QUESTIONS AND PROBLEMS

1. Give some reasons that an anaerobic pond should be deep.
2. Describe the characteristics of each type of stabilization pond.
3. What is the COD of algae if their composition is $C_{106}H_{263}O_{110}N_{16}P$? Assume that P is oxidized to PO_4^{3-}.
4. Using the McGarry–Pescod relation (Eq. 19.3) determine the maximum loading rate that may be applied to the primary facultative pond at a temperature of 20°C. If the waste flow rate is 10 000 m^3/d with a BOD_5 concentration of 400 mg/L, what is the area of the pond?
5. Review and summarize the articles by Gloyna and Tischler (1981), Wittmann (1982), and Gloyna and Tischler (1982), which expand on some of the arguments presented in Section 19.1. Draw your conclusions on stabilization pond systems as a viable treatment.
6. Why does assuming the mixing regime of a pond to be CM provide a safety factor in estimating its performance?
7. Why are correlations between VSS and substrate removal rate weak for stabilization ponds?
8. Design a facultative pond system with four cells to treat a flow of 3 000 m^3/d with a BOD_5 concentration of 275 mg/L. Use a depth of 1.5 m for each cell. Assume that the average winter temperature is in the range of 0–15°C and design the pond surface areas using the average value of the loading rates given in Table 19.2. Then find the predicted effluent BOD_5 at temperatures of 5 and 25°C assuming that rate coefficients are valid at 20°C. (a) Use the CM model with $k = 0.055\,4\ d^{-1}$ and $\theta = 0.987$; and (b) use a PF model with $k = 0.015\,8\ d^{-1}$ and $\theta = 1$.
9. Compare the surface area required in a facultative pond system at 20°C using PF, CM, and Gloyna (Eq. 19.9) models. Assume $f_a = f_S = 1$ in the Gloyna model. There will be three ponds in the system, each with a depth of 1.5 m (4.92 ft). The influent flow rate is 890 m^3/d (0.235 Mgal/d). The influent organics concentration is 150 mg BOD_5/L (unfiltered sample) and the system will achieve a BOD removal of 85%. What is the surface loading rate in each case?
10. Design a stabilization pond system that will contain an anaerobic pond followed by three facultative ponds and two maturation ponds. The maturation ponds will be operated in parallel but the other ponds are operated in series. The design temperature is 12°C. The influent BOD_5 is 520 mg/L and the flow rate is 1 700 m^3/d. Assume that a BOD_5 removal of 40% is achieved in the anaerobic pond. Base other design details of the system on typical criteria given in the text. The residence time in a maturation pond is 24 h. Generally use reasonable loading rate criteria.
11. How is nitrogen removed in stabilization pond systems?
12. What is the lagoon temperature in a 2.7-m-deep aerated lagoon with a surface area of 1.1