CHAPTER 3

DESIGN OF MUNICIPAL WASTEWATER TREATMENT PONDS

3.1 INTRODUCTION

Wastewater treatment ponds existed and provided adequate treatment long before they were acknowledged as an "alternative" technology to mechanical plants in the United States. With legislative mandates to provide treatment to meet certain water quality standards, engineering specifications designed to meet those standards were developed, published and used by practitioners. The basic designs of the various pond types are presented in this chapter. Design equations and examples are found in the Appendix C.

3.2 ANAEROBIC PONDS

An anaerobic pond is a deep impoundment, essentially free of DO. The biochemical processes take place in deep basins, and such ponds are often used as preliminary treatment systems. Anaerobic ponds are not aerated, heated or mixed.

Anaerobic ponds are typically more than eight feet deep. At such depths, the effects of oxygen (O_2) diffusion from the surface are minimized, allowing anaerobic conditions to dominate. The process is analogous to that of a single-stage unheated anaerobic digester. Preliminary treatment in an anaerobic pond includes separation of settleable solids, digestion of solids and treatment of the liquid portion. They are conventionally used to treat high strength industrial wastewater or to provide the first stage of treatment in municipal wastewater pond treatment systems.

Anaerobic ponds have been especially effective in treating high strength organic wastewater. Applications include industrial wastewater and rural community wastewater treatment systems that have a significant organic load from industrial sources. BOD_5 removals may reach 60 percent. The effluent cannot be discharged due to the high level of BOD_5 that remains. Anaerobic ponds are not an appropriate design for locations that do not have sufficient land available. The potential to give off odors, if not properly managed, makes them less a reliable choice for municipal wastewater treatment. Finally, the anaerobic process may require long retention times, especially in cold climates, as anaerobic bacteria are inactive below 15° C. As a result, anaerobic ponds are not widely used for municipal wastewater treatment in the northern United States.

Because anaerobic ponds are deep and generally have a relatively longer hydraulic residence time (HRT), so solids settle, retained sludge is digested, and BOD_5 concentration is reduced. Raw wastewater enters near the bottom of the pond and mixes with the active microbial mass in the sludge blanket. Anaerobic conditions prevail except for a shallow surface layer in which excess undigested grease and scum are concentrated. Sometimes aeration is provided at the surface to control odors. An impervious crust that retains heat and odors will develop if surface aeration is not provided. The discharge is located near the side opposite the influent. Anaerobic ponds are usually followed by aerobic or facultative ponds to provide additional treatment.

The anaerobic pond is usually preceded by a bar screen and a Parshall flume with a flow recorder to determine the inflow. A cover can be provided to trap and collect CH_4, a by-product of the process, for use elsewhere.

3.2.1 Microbiology

Anaerobic microorganisms convert organic materials into stable products, such as CO_2 and CH_4. The degradation process involves two separate but interrelated phases: acid formation and methane production. During the acid phase, bacteria convert complex organic compounds (carbohydrates, fats, and proteins) to simple organic compounds, mainly short-chain volatile organic acids (acetic, propionic, and lactic acids). The anaerobic bacteria involved in this phase are called "acid formers," and are classified as non-methanogenic microorganisms. During this phase, the chemical oxygen demand (COD) is low and BOD_5 reduction occurs, because the short-chain fatty acids, alcohols, and other organic compounds can be used by many aerobic microorganisms.

The methane production phase involves an intermediate step. First, bacteria convert the short-chain organic acids to acetate, hydrogen gas (H_2), and CO_2. This intermediate process is referred to as acetogenesis. Subsequently, several species of strictly anaerobic bacteria called "methane formers" convert the acetate, H_2, and CO_2 into CH_4 through one of two major pathways. This process is referred to as methanogenesis. During this phase, waste stabilization occurs, indicated by the formation of CH_4. The two major pathways of methane formation are

1) the breakdown of acetic acid to form methane and carbon dioxide:

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad (3\text{-}1)$$

and

2) the reduction of carbon dioxide by hydrogen gas to form methane:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2\,H_2O. \qquad (3\text{-}2)$$

3.2.2 Equilibrium

When the system is working properly, the two phases of degradation occur simultaneously in dynamic equilibrium. The volatile organic acids are converted to methane at the same rate that they are formed from the more complex organic molecules. The growth rate and metabolism of the methanogenic bacteria can be adversely affected by small fluctuations in *p*H substrate concentrations and temperature, but the performance of acid-forming bacteria is more tolerant of a wide range of conditions. When anaerobic ponds are stressed by shock loads or temperature fluctuations, CH_4 bacteria activity occurs more slowly than the acid formation and an imbalance occurs. Intermediate volatile organic acids accumulate and the *p*H drops. The methanogens are further inhibited and the process eventually fails without corrective action. For this reason, the CH_4 formation phase is the rate-limiting step and must not be inhibited. For an anaerobic pond to function properly, the design must incorporate the limiting characteristics of these methanogens.

3.2.3 Establishing and Maintaining Equilibrium

The system must operate at conditions favorable for the performance of methanogenic bacteria. Ideally, temperatures should be maintained within the range of 25 to 40° C. Anaerobic activity decreases rapidly at temperatures below 15° C, and virtually ceases when water temperature drops below freezing (0^{o} C). The *p*H value should range from 6.6 to 7.6, and should not drop below 6.2 as CH_4 bacteria cannot function below this level. Sudden fluctuations of *p*H will upset methanogenic activity and inhibit pond performance. Alkalinity should range from 1,000 to 5,000 mg/L.

Volatile acid concentration is an indicator of process performance. Ideally, volatile acid concentrations will be low if the pond system is working properly and dynamic equilibrium between acid formation and consumption is maintained. As a general rule, concentrations should be less than 250 mg/L. Inhibition occurs at volatile acid concentrations in excess of 2,000 mg/L. Table 3-1 presents optimum and extreme operating ranges for CH_4 formation. The rate of CH_4 formation drops dramatically outside these ranges. In addition to adhering to these guidelines, sufficient nutrients, such as *N* and *P* must be available. Concentrations of inhibitory substances, including NH_3 and calcium, should be kept to a minimum. High concentrations of these inhibitors will reduce biological activity. Concentration of free NH_3 in excess of 1,540 mg/L will result in severe toxicity, but concentrations of NH_4^+ must be greater than 3,000 mg/L to produce the same effect. Maintaining a *p*H of 7.2 or below will ensure that most NH_3 will be in the form of NH_4^+, so that higher concentrations can be tolerated with little effect. Table 3-2 provides guidelines for acceptable ranges of other inhibitory substances.

Table 3-1. Ideal Operating Ranges for Methane Fermentation.

Variable	Optimal	Extreme
Temperature, °C	30-35	25-40
*p*H	6.8-7.4	6.2-7.8
Oxidation-Reduction Potential, MV	-520 to -530	-490 to -550
Volatile Acids, mg/L as Acetic	50-500	2000
Alkalinity, mg/L as $CaCO_3$	2000-3000	1000-5000

Table 3-2. Concentrations of Inhibitory Substances (Parkin and Owen, 1986.)

Substance	Moderately Inhibitory (mg/L)	Strongly Inhibitory (mg/L)
Sodium	3,500-5,500	8,000
Potassium	2,500-4,500	12,000
Calcium	2,500-4,500	8,000
Magnesium	1,000-1,500	3,000
Sulfides	200	>200

Anaerobic ponds produce undesirable odors unless provisions are made to oxidize the escaping gases. Gas production must be minimized (sulfate [SO_4^{-2}]) concentration must be reduced to less than 100 mg/L) or aeration should be provided at the surface of the pond to oxidize the escaping gases. Aerators must not introduce DO to depths below the top 0.6 - 0.9 m (2 - 3 ft) so that anaerobic activity at depth is not inhibited.

Another option is to locate the pond in a remote area. A relatively long detention time is required for organic stabilization due to the slow growth rate of the CH_4 formers and sludge digestion. Wastewater seepage into the groundwater may be a problem. Providing a liner for the pond can help avoid this problem.

Advantages and Disadvantages

The advantages of anaerobic ponds are several: sludge removal is infrequently needed; 80-90 percent BOD_5 removal can be expected; the energy requirements to run the plant are low or none; and operation and maintenance (O&M) is relatively uncomplicated.

On the other hand, they are not designed to produce effluent that can be discharged; the ponds can emit unpleasant odors; and the rate of treatment is dependent on climate and season.

3.2.4 Design Criteria

The design of anaerobic ponds is not well defined and a widely accepted overall design equation does not exist. Design is often based on organic loading rates, surface or volumetric loading rates and HRT derived from pilot plant studies and observations of existing operating systems. States in which ponds are commonly used often have regulations governing their design, installation, and management. For example, state regulations may require specific organic loading rates, detention times, embankment slope ratio of 1 to 3 to 1 to 4, and maximum allowable seepage of 1 to 6 mm/d.

3.2.5 Performance

System performance depends on loading, temperature, and whether the *p*H is maintained within the optimum range. Tables 3-3 and 3-4 show expected removal efficiencies for municipal wastewaters. In cold climates, detention times as great as 50 days and volumetric loading rates as low as 0.04 kg $BOD_5/m^3/d$ may be required to achieve 50 percent reduction in BOD_5. Effluent TSS will range between 80 and 160 mg/L. The effluent is not suitable for direct discharge to receiving waters. Pond contents that are black indicate that it is functioning properly.

Table 3-3. BOD_5 Reduction as a Function of Detention Time for Temperatures Greater than 20 °C (World Health Organization, 1987)

Detention Time (Days)	BOD_5 Reduction (Percent)
1	50
2.5	60
5	70

Table 3-4. BOD_5 Reduction as a Function of Detention Time and Temperature (World Health Organization, 1987)

Temperature (°Celsius)	Detention Time (Days)	BOD_5 Reduction (Percent)
10	5	0-10
10-15	4-5	30-40
15-20	2-3	40-50
20-25	1-2	40-60
25-30	1-2	60-80

3.2.6 Operation and Maintenance

Operation and maintenance requirements of an anaerobic pond are minimal. A daily grab sample of influent and effluent should be taken and analyzed to ensure proper operation. Aside from sampling, analysis, and general upkeep, the system is virtually maintenance-free. Solids accumulate in the pond bottom and require removal infrequently (5-10 years), depending on the amount of inert material in the influent and the temperature. Sludge depth should be measured annually.

3.2. Costs

The primary costs associated with constructing an anaerobic pond are the cost of the land, building earthwork appurtenances, constructing the required service facilities, and excavation. Costs for forming the embankment, compacting, lining, service road and fencing, and piping and pumps must also be considered. Operating costs and energy requirements are minimal.

3.2.8 Design Models and Example Calculations

Anaerobic treatment ponds are typically designed on the basis of volumetric loading rate and HRT. Although often done, it is probably inaccurate to design on the basis of surface loading rate. Design should be based on the volumetric loading rate, temperature of the liquid, and the HRT. Areal loading rates that have been used around the world are shown in Table 3-5. It is possible to approximate the volumetric loading rates by dividing by the average depth of the ponds and converting to the proper set of units.

In climates where the temperature exceeds 22 °C, the following design criteria should yield a BOD_5 removal of 50 percent or better (World Health Organization, 1987).

Volumetric loading up to 300 g $BOD_5/m^3/d$
HRT of approximately 5 d
Depth between 2.5 and 5 m

In cold climates, detention times as great as 50 d and volumetric loading rates as low as 40 g $BOD_5/m^3/d$ may be required to achieve 50 percent reduction in BOD_5.

Table 3-5. Design and Operational Parameters for Anaerobic Ponds Treating Municipal Wastewater (See p. xiv for Conversion Table)

ALR BOD_5 lbs/ac/d		Est. VLR lbs/1000 ft^3		Removal Percent		Depth	HRT	Refs.
Summer	Winter	Summer	Winter	Summer	Winter	Ft	D	
360		2.34		75		3-4		Parker, 1970
280		1.84		65		3-4		Parker, 1970
100		0.66		86		3-4		Parker, 1970
170		1.11		52		3-4		Parker, 1970
560	400	3.67	2.62	89	60	3-4		Parker, 1970
400	100			70				Oswald, 1968 b
900-1200	675	5.17-6.89	3.88	60-70		3-5	2-5	Parker et al., 1959
						8-10	30-50	Eckenfelder, 1961
220-600			0.51-1.38				15-160	Cooper, 1968
500			1.15	70		8-12	5	Oswald et al., 1967
						8-12	2 (s) 5 (w)	Malina and Rios, 1976

ALR = areal loading rate
VLR = volumetric loading rate
See p. xiv for conversion table.

An example of an approach to the design of anaerobic ponds has been presented by Oswald (1996) (Figure 3-1). In his Advanced Integrated Wastewater Pond System® (see Chapter 4), Oswald incorporates a deep anaerobic pond within a facultative pond. The anaerobic pond design is based on organic loading rates that vary with water temperature in the pond, and the design is checked by determining the volume of anaerobic pond provided per capita, which is one of the methods used for the design of separate anaerobic digesters. An example of this design approach is presented in Appendix C (Example C-3-1), along with another example using volumetric loading or detention times (see Example C-3-2) (Crites et al., 2006).

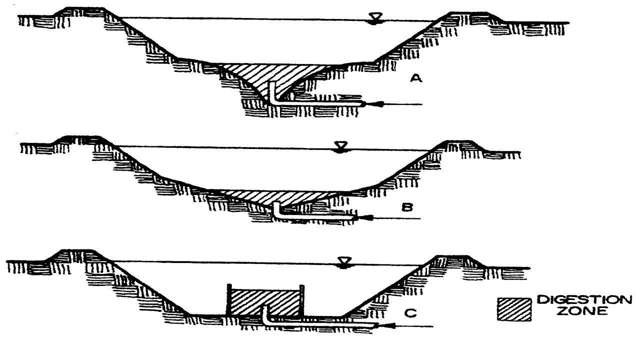

Figure 10-1. Methods of Creating a Digestion Chamber in the Bottom of an Anaerobic Lagoon (Oswald, 1968)

Figure 3-1. Method of creating a digestion chamber in the bottom of an anaerobic pond (Oswald, 1968).

3.3 FACULTATIVE PONDS

3.3.1 Description

The technology associated with conventional facultative ponds to treat municipal and industrial wastewater has been in widespread use in the United States for 100 years. These ponds are usually 1.2 - 2.4 m in depth and are not mechanically mixed or aerated. The layer of water near the surface contains sufficient DO from atmospheric re-aeration and photosynthetic oxygenation by microalgae growing in the photic zone to support the growth of aerobic and facultative bacteria that oxidize and stabilize wastewater organics. The bottom layer of a conventional facultative pond includes sludge deposits that are decomposed by anaerobic bacteria. These shallow ponds tend to integrate carbon and primary solids undergoing acetogenic fermentation but only intermittent methane fermentation. The intermediate anoxic layer, called the facultative zone, ranges from aerobic near the top to anaerobic at the bottom. These three strata or layers may remain stable for months due to temperature-induced water density differentials, but normally twice a year during the spring and fall seasons, conventional facultative ponds will overturn, and the three strata will mix bottom to top, top to bottom. This dimictic overturn inhibits CH_4 fermentation by O_2 intrusion into the bottom anaerobic stratum, and, as a result, *C* is integrated rather than being converted into biogas (Oswald et al., 1994).

The presence of algae, which release O_2 as they disassociate water molecules photochemically to assimilate hydrogen during photosynthesis, is essential to the successful performance of conventional, as well as advanced, facultative ponds. On warm, sunny days, the O_2 concentration in the aerobic zone can exceed saturation levels. As the algae take up CO_2, the *p*H of the near-surface water can exceed 10, creating conditions favorable for ammonia removal via volatilization (see Chapter 5). At night, when the algae are not photosynthesizing, O_2 levels decrease. Oxygen and *p*H levels shift together from a maximum in daylight hours to a minimum at night. The O_2 in the upper layers of the facultative pond is used by aerobic and facultative bacteria to stabilize organic material. Anaerobic fermentation, which takes place in the absence of O_2, is the dominant activity in the bottom layer of the pond. In cold climates, both oxygenation and fermentation reaction rates are significantly slower during the winter and early spring so that effluent quality may be reduced to the equivalent of primary effluent when an ice cover persists on the water surface. As a result, northern United States and Canadian provinces prohibit discharge from facultative ponds in the winter months.

3.3.2 Applicability

Conceptually, conventional facultative ponds are well suited for rural communities and industries where land costs are not a limiting factor. Conventional facultative ponds have been used to treat raw, screened, or primary settled municipal wastewater as well as higher strength biodegradable industrial wastewater. They represent a reliable and easy-to-operate process that is cost effective.

3.3.3 Advantages and Disadvantages

The advantages of facultative ponds include infrequent need for sludge removal; effective removal of settleable solids, BOD_5, pathogens, fecal coliform, and, to a limited extent, NH_3. They are easy to operate and require little energy, particularly if designed to operate with gravity flow.

The disadvantages include higher sludge accumulation in shallow ponds or in cold climates and variable seasonal NH_3 levels in the effluent. Emergent vegetation must be controlled to avoid creating breeding areas for mosquitoes and other vectors. Shallow ponds require relatively large areas. During spring and fall dimictic turnover, odors can be an intermittent problem.

3.3.4 Design Criteria

Facultative pond systems may be relatively simple mechanically, but the biological and chemical reactions taking place within them are more complex than those in conventional mechanical wastewater treatment systems. Typical design features needed to operate facultative ponds include the use of linings to control seepage to groundwater and emergent plant growth; proper design and location of inlet and outlet structures; and hydraulic controls, floating dividers, and baffles.

Many existing conventional facultative ponds are large, single-cell systems with inlets located near the center of the cell. This configuration can result in short-circuiting and ineffective use of the system design volume. A multiple-cell system with at least four cells in series, with appropriate inlet and outlet structures, is strongly recommended (Mara and Cairncross, 1989).

Most states have design criteria that specify the areal or surface organic loading rate expressed in kg/ha/d or lbs/ac/d and/or the hydraulic loading rate expressed in m/d or ft/d residence time. Typical organic loading values range from 15 - 80 kg/ha/d. Detention times range from 20 - 180 days, and can approach 200 days in northern climates where discharge restrictions prevail. Effluent $BOD_5 < 30$ mg/L can usually be achieved, while effluent TSS may range from < 30 mg/L to more than 100 mg/L, depending on the algal concentrations and discharge structure design.

A number of empirical and rational models exist for the design of simple conventional and in-series facultative ponds. These include first order plug flow, first order complete mix, and models proposed by Gloyna (1976), Marais (1961), Oswald (1968b), and Thirumurthi (1974).

All provide reasonable designs, as long as the basis for the formula is understood, appropriate parameters are selected, and the hydraulic detention and sludge retention characteristics of the system are known. This last element is of critical importance because short-circuiting in a poorly designed cell can result in detention time of 50 percent or less than the theoretical design value.

3.3.5 Design Methods

3.3.5.1 Areal Loading Rate Method

A series of detailed evaluations of facultative pond systems conducted by EPA remains a useful data set for pond systems performance in the United States (U.S. EPA, 1975). Studies of systems in other countries bring the literature up to date (Racault and Boutin, 2001; Kotsovinos et al., 2004; Oliveira and von Sperling, 2008; von Sperling and Oliveira, 2009). A comparison of the state design criteria for each location and actual design values for organic loading and HRT for four facultative pond systems evaluated by the EPA (Middlebrooks et al., 1982) are presented in Table 3-6. Many of the design flaws in the systems referenced in Table 3-6 have been corrected since 1983.

The following surface organic loading rates for various climatic conditions are recommended for use in designing facultative pond systems. For average winter air temperatures above 15 °C, a BOD_5 loading rate range of 45 - 90 kg/ha/d is recommended. When the average winter air temperature ranges between 0 - 15 °C the organic loading rate should range between 22 - 45 kg/ha/d. For average winter temperatures below 0 °C the organic loading rates should range from 11 - 22 kg/ha/d.

A review of design standards in 2006 showed that most states have design criteria for organic loading and/or HRT for facultative ponds with many now incorporating NH_4 conversion and P removal requirements. The principal changes since a survey by Canter and Englande (1970) are the nutrient removal requirements.

Table 3-6. Design and Performance Data from U.S. EPA Pond Studies (Middlebrooks et al., 1982).

Location	Organic Load (kg BOD_5/ha/d)			Theoretical Detention Time			
	State Design	Design	Actual	State Design	Design	Actual	Month 30 mg/L exceeded
P'borough[1]	39.3	19.6	16.2	None	57	107	10, 2,3,4
Kilmichael[2]	56.2	43.0	17.5	None	79	214	11, 7
Eudora[3]	38.1	38.1	18.8	None	47	231	3, 4, 8
Corinne[4]	45.0*	36.2	29.7*	180	180	70	None
			14.6**			88***	

[1]New Hampshire; [2]Mississippi; [3]Kansas; [4]Utah.
*Primary cell; ** Entire system; ***Estimated from dye study.

The BOD_5 loading rate in the first cell is usually limited to 40 kg/ha/d or less, and the total HRT in the system is 120 - 180 days in climates where the average winter air temperature is below 0

°C. In mild climates, where the winter temperature is greater than 15 °C, loadings on the primary cell can be 100 kg/ha/d (see Example C-3-3 in Appendix C).

3.3.5.2 Comparison of Facultative Pond Design Models

Because there are many possible approaches to the design of facultative ponds and given the lack of adequate performance data for the latest designs, it is not possible to recommend one approach over the others. An evaluation of the design methods presented above, with operational data referenced in Table 3-6 did not indicate that any of the models are superior to the others in predicting performance (Middlebrooks, 1987). Other reviews of facultative pond systems based on more limited data sets have reached similar conclusions (Pearson and Green, 1995). Each of the models was used to design a facultative pond for the conditions presented in Example C-3-3; the results are summarized at the end of the example (see Appendix C).

While it is difficult to make direct comparisons, an examination of the HRTs and total volume requirements calculated by all of the methods show considerable consistency if the reaction rates are selected carefully. The major limitation of all these methods is the selection of a reaction rate constant or other factors in the equations. Appropriate reaction rates must be selected, but if the pond hydraulic system is designed and constructed so that the theoretical HRT is approached, reasonable success can be assured with all of the design methods. Short-circuiting is the greatest deterrent to consistent pond performance. The importance of the hydraulic design of a pond system cannot be overemphasized.

The surface loading rate approach to design requires a minimum of input data, and is based on operational experiences in various geographical areas of the United States. It is probably the most conservative of the design methods, but the hydraulic design should be included as well.

The Gloyna loading design method achieves 80 to 90 percent BOD_5 removal efficiency, and it assumes that solar energy for photosynthesis is above the saturation level. Provisions for removal outside this range are not anticipated; however, adjustments for other solar conditions can be calculated. Mara (1975) provides a detailed critique of the method.

3.3.6 Performance

Overall, facultative pond systems are simple to operate, but may be variable in performance; BOD_5 removal can range up to 75 percent; TSS may exceed 150 mg/L; NH_3 removal can be significant (up to 90 percent) depending on temperature, *p*H and detention time in the system, except in winter; approximately 50 percent P removal can be expected under high *p*H conditions; and pathogens and coliform removal is effective, depending on temperature and detention time.

Limitations to be considered include the fact that algae in the effluent may increase TSS above the 30 mg/L limit for TSS; low temperatures and ice formation will limit process efficiency; and odors may be a problem in the spring and fall.

3.3.7 Operation and Maintenance

Most facultative ponds are designed to operate by gravity flow. The system requires less maintenance and has lower associated energy costs because pumps and other electrically powered devices may not be required. Although some analysis is essential to ensure proper operation, an extensive sampling and monitoring program is usually not necessary. Regular observation of impoundment earth works must be performed to monitor for excavation by burrowing animals. See Chapter 9 for more details on operation and maintenance.

3.3.8 Common Modifications

A common modification to facultative ponds is to operate them in the controlled discharge mode, where discharge is prohibited during the winter months in cold climates and/or during peak algal growth periods in the summer. In this approach, each cell in the system is isolated and discharged sequentially. A similar modification, the hydrograph controlled release (HCR), retains treated wastewater in the pond until flow volume and conditions in the receiving stream are adequate for discharge. A recently developed physical modification uses plastic curtains, supported by floats and anchored to the bottom, to divide ponds into multiple cells and/or to serve as baffles to improve hydraulic conditions. Another modification uses a floating plastic grid to support the growth of duckweed (*Lemna* spp.) on the surface of the final cell in the pond system, which restricts light penetration and reduces algal growth (with sufficient detention time, >20 d), improving the final effluent quality. These types of modifications are discussed in detail in Chapter 7.

3.3.9 Costs

Cost information for facultative ponds varies significantly. Construction costs include land purchase, excavation, grading, berm construction, and inlet and outlet structures. If the soil is permeable, an additional cost for lining should be considered. See Chapter 8 for discussion of costs associated with construction of pond systems.

3.4 AERATED POND SYSTEMS

3.4.1 Partial Mix Aerated Ponds

Aerobic ponds are classified by the amount and source of O_2 supplied. In aerated systems, O_2 is supplied mainly through mechanical or diffused aeration rather than by algal photosynthesis. The submerged systems can include perforated tubing or piping, with a variety of diffusers attached. A partial mix system provides only enough aeration to satisfy the O_2 requirements of the system. It does not provide energy to keep all solids in suspension. In some cases, the initial cell in a system might be a complete mix unit followed by partial mix and settling cells. A complete mix system requires about 10 times the amount of energy needed for a similarly sized partial mix system.

Some solids in partial mix ponds are kept in suspension to contribute to overall treatment. This allows for anaerobic fermentation of the settled sludges. Partial mix ponds are also called facultative aerated ponds and are generally designed with at least three cells in series; total detention time depends on water temperature. The ponds are constructed to have a water depth of up to 6 m to ensure maximum O_2 transfer efficiency. In most systems, aeration is not applied uniformly over the entire system.

Typically, the most intense aeration (up to 50 percent of the total required) is used in the first cell. The final cell may have little or no aeration to allow settling to occur. In some cases, a small separate settling pond is provided after the final cell. Diffused aeration equipment typically provides about 3.7 - 4 kg O_2/kW/hr and mechanical surface aerators are rated at 1.5 - 2.1 kg O_2/kW/hr. Consequently, diffused systems are somewhat more efficient than non-aerated ponds, but also require a significantly greater installation and maintenance effort.

Aerobic ponds can reliably produce an effluent to achieve BOD_5 and TSS < 30 mg/L if a settling pond is in place at the end of the system. Additionally, significant nitrification will occur during the summer if there is adequate DO. Many systems designed only for BOD_5 removal fail to meet discharge standards during the summer because of a shortage of DO. Both nitrification of NH_3 and BOD_5 removal require O_2. To achieve regulatory limits for the two parameters in heavily loaded systems, pond volume and aeration capacity beyond that provided for BOD_5 removal alone are required. It is generally assumed that 1.5 kg of O_2 will treat 1 kg of BOD_5. About 5 kg of O_2 are theoretically required to convert 1 kg of NH_3 to NO_3^-.

3.4.1.1 Applicability

Aerated ponds are well suited for small communities and industries and require less land. They are usually designed with a shorter retention time. They have been used to treat raw, screened or primary settled municipal wastewater, as well as higher strength biodegradable industrial wastewater. The process is reliable, relatively easy to operate and cost effective.

3.4.1.2 Advantages and Disadvantages

The advantages include reliable BOD_5 removal; significant nitrification of NH_3 possible with sufficient mean cell resident time; treatment of influent with higher BOD_5 in less space; and reduced potential for unpleasant odors.

Aerated ponds are more complicated to design and construct, which increases capital and O&M costs. A larger staff is needed for whom training must be provided on a regular basis. Finally, sludge removal is more frequent and requires secondary treatment for disposal off-site.

3.4.1.3 Design Methods

The basic approach to the design of partial mix aerobic ponds has not changed since the early 1980’s. The most notable innovations have been the placement of floating plastic partitions in the ponds to improve the hydraulic characteristics and the development of a wider selection of more efficient aeration equipment (Water Environment Federation, 2001). Given the importance of the hydraulic characteristics, retaining redundancy in the design of aerobic pond systems is still strongly encouraged. Operation and maintenance costs associated with aerobic pond systems often are not included when communities compare system options. The initial cost of a system built without redundancy is lower in the short term. Systems that include flexibility in operation in the long run, however, greatly reduce the actual cost to the environment and the owner.

In partial mix systems, the aeration serves to provide only an adequate O_2 supply, and there is no attempt to keep all of the solids in suspension. Although some of the solids are suspended, anaerobic degradation of the organic matter that settles does occur.

3.4.1.4 Partial Mix Design Model

Although the pond is partially mixed, it is conventional to estimate the BOD_5 removal using a complete mix model and first order reaction kinetics. Studies by Middlebrooks et al. (1982) have shown that a plug flow model and first order kinetics more closely predict the performance of these ponds when either surface or diffused aeration is used. However, most of the ponds evaluated in this study were lightly loaded and the calculated reaction rates are very conservative, as it seems that the rate decreases as the organic loading decreases (Neel et al., 1961). Without additional data to support theoretical design reaction rates, it is necessary to design partial mix ponds using complete mix kinetics.

The design model using first order kinetics and operating *n* number of equal sized cells in series is given by Equation 3-3 (Middlebrooks et al. 1982; 10 States Standards, 2004; Water Environment Federation, 2001; Crites et al., 2006).

$$\frac{C_e}{C_0} = \frac{1}{[1 + (kt/n)]^n} \qquad (3\text{-}3)$$

Where:

C_n = effluent BOD_5 concentration in cell *n*, mg/L
C_o = influent BOD_5 concentration, mg/L
k = first order reaction rate constant /d
= 0.276 day^{-1} at 20° C (assumed to be constant in all cells)
t = total hydraulic residence time in pond system, d
n = number of cells in the series

If other than a series of equal volume ponds are to be employed and varying reaction rates are expected, the following general equation should be used:

$$\frac{C_n}{C_0} = \left(\frac{1}{1+k_1t_1}\right)\left(\frac{1}{1+k_2t_2}\right)\cdots\left(\frac{1}{1+k_nt_n}\right) \qquad (3\text{-}4)$$

where $k_1, k_2, \ldots k_n$ are the reaction rates in cells 1 through *n* (all usually assumed to be equal without additional data) and $t_1, t_2, \ldots t_n$ are the hydraulic residence times in the respective cells.

Mara (1975) has shown that a number of equal volume reactors in series is more efficient than unequal volumes; however, due to site topography or other factors, there may be sites where it is necessary to construct cells of unequal volume.

3.4.1.5 Temperature Effects

The influence of temperature on the reaction rate is defined by Equation 3-5.

$$k_T = k_{20}\theta^{T_w - 20} \qquad (3\text{-}5)$$

Where:

k_T = reaction rate at temperature T/d
k_{20} = reaction rate at 20° C/d

θ = temperature coefficient = 1.036
T_w = temperature of pond water, °C

The pond water temperature (T_w) can be estimated using the following equation developed by Mancini and Barnhart (1976).

$$T_w = \frac{AfT + QT_1}{Af + Q} \qquad (3\text{-}6)$$

Where:

T_w = pond water temperature, °C
T_a = ambient air temperature, °C
A = surface area of pond, m^2
f = proportionality factor = 0.5
Q = wastewater flow rate, m^3/d

An estimate of the surface area is made based on Equation 3-4, corrected for temperature, and the temperature is calculated using Equation 3-6. After several iterations, when the water temperature used to correct the reaction rate coefficient agrees with the value calculated with Equation 3-6, the detention time in the system can be determined.

3.4.1.6 Selection of Reaction Rate Constants

The selection of a *k* value is the critical decision in the design of any pond system. A design value of 0.12 /d at 20 °C and 0.06/d at 1 °C is recommended by the 10 States Standards (2004). Studies of systems in Texas have empirically derived the value of the temperature coefficient, θ, for soluble organic removal in complete mix ponds to be 1.03-1.04 (Wang and Pereira, 1986.)

3.4.1.7 Influence of Number of Cells

When using the partial mix design model, the number of cells in series has a pronounced effect on the size of the pond system required to achieve the specified degree of treatment. The effect can be demonstrated by rearranging Equation 3-1 and solving for *t*:

$$t = \frac{n}{k}\left[\left(\frac{C_0}{C_n}\right)^{\frac{1}{n}} - 1\right] \qquad (3\text{-}7)$$

All terms in this equation have been defined previously.

3.4.1.8 Pond Configuration

The ideal configuration of a pond designed on the basis of complete mix hydraulics is a circular or square pond. However, even though partial mix ponds are designed using the complete mix model, it is recommended that the cells be configured with a length-to-width ratio of 3:1 or 4:1. This is because it is recognized that the hydraulic flow pattern in partial mix systems more closely resembles the plug flow condition. The dimensions of the cells can be calculated using Equation 3-8.

$$V = [LW + (L - 2sd)(W - 2sd) + 4(L - sd)(W - sd)]\frac{d}{6} \qquad (3\text{-}8)$$

Where:

V = volume of pond or cell, m^3
L = length of pond or cell at water surface, m
W = width of pond or cell at water surface, m
s = slope factor (e.g., with 3:1 slope, s = 3)
d = depth of pond, m

3.4.1.9 Mixing and Aeration

The O_2 requirements control the energy input required for partial mix pond systems. There are several rational equations available to estimate the O_2 requirements for pond systems; these can be found in Benefield and Randall (1980), Gloyna (1976, 1971), and Metcalf and Eddy (1991, 2003). In most cases, partial mix system design is based on the strength of the BOD_5 entering the system. After calculating the required rate of O_2 transfer, information contained in equipment manufacturers' catalogs should be consulted to determine the zone of complete O_2 dispersion by surface, helical, or air gun aerators or the proper spacing of perforated tubing. Schematic sketches of several of the various types of aerators used in pond systems are shown in Figure 3-2A and B. Photographs of installed aeration equipment are shown in Figure 3-3.

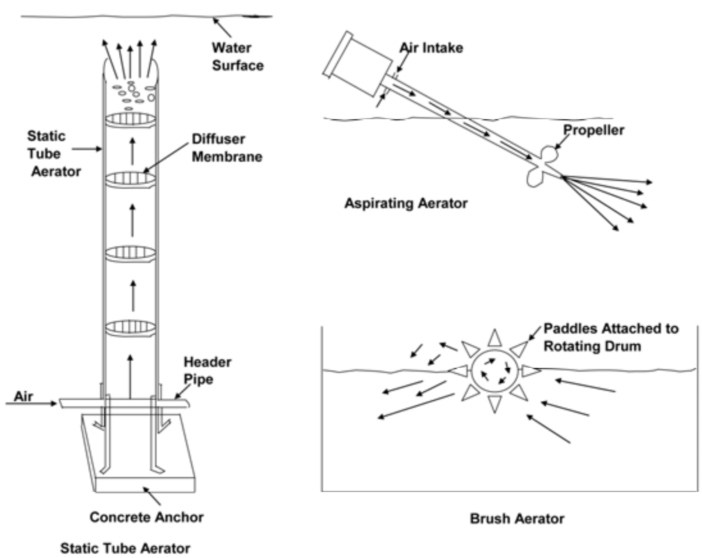

Figure 3-2A. Static Tube, Brush and Aspirating Aerators. (Reynolds and Richards, 1996).

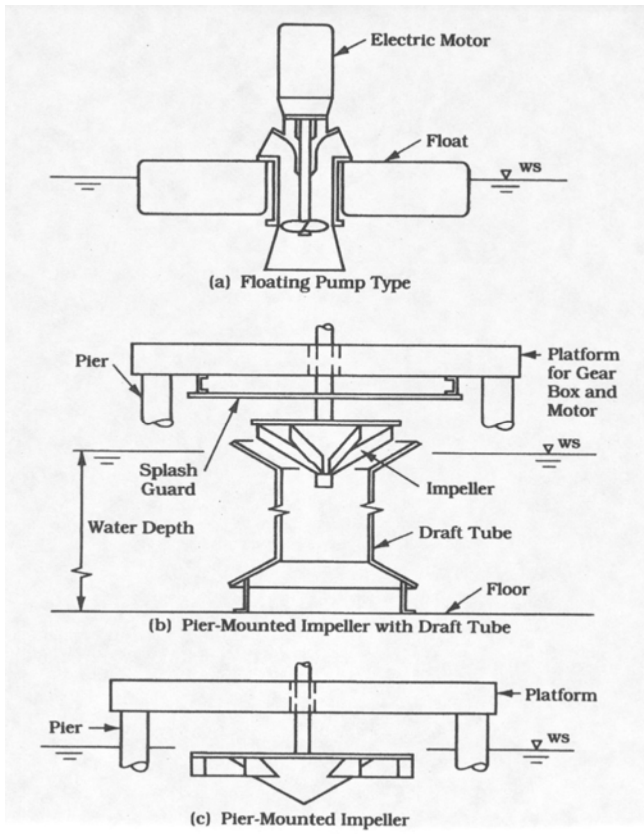

Figure 3-2B. Floating pump, pier-mounted impeller with draft tube and pier-mounted impeller (Reynolds and Richards, 1996).

See Appendix C for mixer and diffuser design calculations.

Surface aeration equipment is subject to potential icing problems in cold climates, but there are many options available to avoid this problem (see Figure 3.3 and Chapter 4). Improvements have been made in fine bubble perforated tubing, but a diligent maintenance program is still the best policy. In the past, a number of systems experienced clogging of the perforations, particularly in hard water areas, and corrective action required purging with *HCl* gas.

Figure 3-3. Floating aerators in summer and winter operation.

The final element recommended in this partial mix aerobic pond system is a settling cell with a 2 d HRT at the average design flow rate.

3.4.1.10 Performance

Reliable BOD_5 removal up to 95 percent can be expected. Effluent TSS can range from 20 to 60 mg/L, depending on the design of the settling basin and the concentration of algae in the effluent. Removal of NH_3 is less effective due to shorter detention times, but nitrification of NH_3 can occur in aerated ponds if the system is designed for that purpose. Phosphorus removal is only 15 - 25 percent. Removal of total and fecal coliform depends on length of detention time and temperature. If effluent limits are < 200 MPN/100 mL, disinfection may be needed.

3.4.1.11 Limitations and Operation and Maintenance

Depending upon the rate of aeration and the environment, ice may form on the surface of aerobic ponds during cold weather. Rates of biological activity slow down during cold weather. If properly designed, a system will continue to function and produce acceptable effluents under these conditions. The potential for ice formation on floating aerators may encourage the use of submerged diffused aeration in very cold climates.

The use of submerged perforated tubing for diffused aeration requires maintenance and cleaning on a routine basis to maintain design rates. There are numerous types of submerged aeration equipment that can be used in warm or cold climates, and these should be considered for all designs. In submerged diffused aeration, the routine application of hydrochloric acid (HCl) gas in the system is used to dissolve accumulated material on the diffuser units. Any earthen structures used as impoundments must be periodically inspected. Typically, operation occurs by gravity flow. Energy is required for the aeration devices, the amount depending on the intensity of mixing desired. Partial mix systems require between 1 - 2 W/m^3 capacity, depending on the depth and configuration of the system. See design example C-3-7 in Appendix C for a method of calculating the energy requirements for partial mix systems.

3.4.1.12 Modifications

One physical modification to an aerobic pond is the use of plastic curtains supported by floats and anchored to the bottom to divide existing ponds into multiple cells and/or serve as baffles to improve hydraulic conditions. A recently developed approach suspends a row of submerged diffusers from flexible floating booms, which move in a cyclic pattern during aeration activity. This treats a larger volume with each aeration line. Effluent is periodically recycled within the system to improve performance. If there is sufficient depth for effective O_2 transfer, aeration is used to upgrade existing facultative ponds and is sometimes used on a seasonal basis during periods of peak wastewater discharge (e.g., seasonal food processing wastes) to the pond.

3.4.1.13 Costs

Construction costs associated with partially mixed aerobic ponds include cost of the land, excavation, and inlet and outlet structures. If the soil where the system is constructed is permeable, there will be an additional cost for lining. Excavation costs vary, depending on whether soil must be added or removed. Operating costs of partial mix ponds include operation and maintenance of surface or diffused aeration equipment.

3.4.2 Complete Mix Aerated Ponds (Subset of Aerated Pond System)

Complete mix systems rely on mechanical aeration to introduce enough O_2 to completely degrade all BOD_5. In addition to that, however, the additional mixing suspends the solid material to enhance biodegradation.

3.4.2.1 Applicability

See Section 3.4.1.1.

3.4.2.2 Advantages/Disadvantages

See Section 3.4.1.2.

3.4.2.3 Design models and example calculations

Complete mix ponds are smaller than partial mix ponds and all solids in the aeration cell are kept in suspension. The system is designed using first order kinetics and a complete mix model. Most states specify the formulation shown in Equation 3-7 and used in the design example to size the aeration cell and specify the size of the settling cell. Typically a plastic, clay or other impervious lining is required to protect groundwater. A multiple cell system with at least three cells in series is recommended, with appropriate inlet and outlet structures to maximize effectiveness of the design volume. Hydraulic residence times are generally are less than 3 d except where high strength wastewaters are treated. An HRT range of 2 - 4 d is recommended so that the microbial community has sufficient time to grow (von Sperling and de Lemos Chernicharo, 2005).

3.4.2.4 Design Equation

The design model using first order kinetics and operating n number of equal sized cells in series is given in Section 3.4 by Equation 3-3 and if a series of non-equal volume ponds or ponds with varying reaction rates are to be designed, use Equation 3-4.

3.4.2.5 Temperature Effects

See Section 3.4.1.5.

3.4.2.6 Selection of Reaction Rate Parameters

See Section 3.4.1.6.

3.4.2.7 Influence of Number of Cells

See Section 3.4.1.7. An example (C-3-4) can be found in Appendix C.

3.4.2.8 Pond Configuration

The ideal configuration of a pond designed on the basis of complete mix hydraulics is a circular or a square pond; however, it is recommended that the cells be configured with a length to width ratio of 3:1 or 4:1 because the hydraulic flow pattern in complete mix systems actually more closely resembles the plug flow model. The dimensions of the cells can be calculated using Equation 3-8 in Section 3.4.1.8.

3.4.2.9 Mixing and Aeration

The mixing requirements usually control the energy input required for complete mix pond systems. There are several rational equations available to estimate the O_2 requirements for pond systems (see Section 3.4.1.9 for references). Complete mix systems are designed by estimating the strength of the BOD_5 entering the system and then calculated to ensure that adequate energy is available to provide complete mixing. Once the required rate of O_2 transfer is known, the equipment manufacturers' catalogs should be consulted to determine the zone of complete mixing and O_2 dispersion. The aerators used in complete mix systems are the same as those used in partial mix systems.

Equation 3-9 is used to estimate O_2 transfer rates.

$$N = \frac{N_a}{\alpha\left[\frac{(C_{sw} - C_L)}{C_s}\right](1.025)^{(T_W - 20)}} \quad (3\text{-}9)$$

where

N = equivalent O_2 transfer to tap water at standard conditions, kg/hr

N_a = O_2 required to treat the wastewater, kg/hr (usually taken as 1.5 x the organic loading entering the cell)

a = (O_2 transfer in wastewater)/(O_2 transfer in tap water) = 0.9

C_L = minimum DO concentration to be maintained in the wastewater, assume 2 mg/L

C_s = O_2 saturation value of tap water at 20 °C and one atmosphere pressure = 9.17 mg/L

T_w = wastewater temperature, °C

C_{sw} = $\beta(C_{ss})P$ = O_2 saturation value of the waste, mg/L

β = (wastewater saturation value)/(tap water O_2 saturation value)

C_{ss} = tap water O_2 saturation value at temperature T_w

P = ratio of barometric pressure at the pond site to barometric pressure at sea level, assume 1.0 for an elevation of 100 m

Equation 3-6 can be used to estimate the water temperature in the pond during the summer months, which is the most active period of biological activity. However, as energy to provide complete mixing is assumed to be available, DO should be at adequate levels throughout the year. The complete mix design procedure is illustrated in Example 3-5 found in Appendix C. The four-cell system can be simulated by using floating plastic partitions (see Chapter 4).

3.4.2.10 Performance

See Section 3.4.1.10.

3.4.2.11 Modifications

There are many configurations of complete mix pond systems. Examples that will be discussed in Chapter 4 include the High-Performance Aerated Pond Systems and the BIOLAC® Process.

An examination of Example C-3-3 (Appendix C) will show the similarity between the design for the High-Performance Aerated Pond System and the complete mix design when the final three cells of the complete mix design are supplied with only enough DO to meet the BOD_5. This is not to imply that the designs are identical, but only to point out that they have some common features.

3.4.2.12 Costs

See Section 3.4.1.12.