CHAPTER 4

PHYSICAL DESIGN AND CONSTRUCTION

4.1 INTRODUCTION

No matter how carefully coefficients are evaluated and biological or kinetic models reviewed, if sufficient consideration is not given to optimization of the pond layout and construction, the actual efficiency of the system may be far less than the calculated efficiency. The biological factors affecting wastewater pond performance must be understood so that a reasonable estimate of the hydraulic residence time required to achieve a specified efficiency is incorporated into the design. But it is the physical factors, such as length to width ratio, placement of inlet and outlet structures and redundancy in design that determine the actual treatment efficiency that can be achieved (Crites et al., 2006; Shilton, 2005).

The danger of groundwater contamination frequently imposes seepage restrictions, necessitating lining or sealing the pond. Reuse of the pond effluent in dry areas where all water losses are to be avoided may also dictate the use of linings. Layout and construction criteria should be established to reduce dike erosion from wave action, weather and burrowing animals. Transfer structure placement and size affect flow patterns within the pond and determine operational ability to control the water level and discharge rate. These important physical design considerations are discussed in the following sections.

4.2 DIKE CONSTRUCTION

Dike stability is most often affected by erosion caused by wind-driven wave action or rain and rain-induced weathering. Dikes may also be destroyed by burrowing animals. A good design with proper maintenance, will anticipate these problems and provide a stable, reliable system.

4.2.1 Wave Protection

Erosion protection should be provided on all slopes; however, if winds are predominantly from one direction, protection should be enhanced for those areas that receive the full force of the wind-driven waves. Protection should always extend from at least 0.3 m below the minimum water surface to at least 0.3 m above the maximum water surface (U.S. EPA, 1977b; Kays, 1986; U.S. Department of Interior [USDI], 2001). Wave height is a function of wind velocity and fetch (the distance over which the wind acts on the water). The size of riprap needed depends on the fetch length (Uhte, 1974; Kays, 1986). Riprap varies from river run rocks that are 15 - 20 cm to quarry boulders that are 7 - 14 kg. Uniformly graded river run material, when used for riprap, can be quite unstable. River run rocks, if not properly mixed with smaller material and carefully placed, can be loosened by wave action and slip down the steep sloped dikes. Broken concrete pavement can often be used for riprap but can make mechanical weed control difficult. Asphalt, concrete, fabric, and low grasses can also be used to provide protection from wave action. When riprap is used for wave protection, the designer must take into consideration its effect on weed and animal control and routine dike maintenance.

4.2.2 Weather Protection

Dike slopes must be protected from weather induced erosion as much as from wave erosion in many areas of the country. The most common method of weather erosion protection employs grass when large dike areas are involved. Because variations in depth develop in total containment ponds, they often have large sloped dike areas that cannot be protected in a more cost-effective way. Ponds that have only minimum freeboard and constant water depth may be protected more cost-effectively if the riprap is carried right to the top of the slope where it can serve as wave and weather protection.

In some cases climate and soil conditions are suitable for completely bare dike slopes without major weather erosion problems. Figure 4-1 shows the erosion effects on the bare slopes of a treatment pond.

Weather caused erosion, unlike wave erosion, can also affect the top and outside slopes of the pond diking system. The designer should make sure that the all-weather road system for the top of the dike is of sufficient width to allow traffic to pass over every part of the surface. Too narrow a road will result in ruts that can create runoff erosion problems in areas of high rain intensity. Final grading should be specified to minimize rutting and frequent maintenance should be required to control surface runoff and erosion.

It is also necessary to protect the exterior surface of dikes. A thin layer of gravel may be used; placement of topsoil and seeding for native groundcover is recommended. Local highway department experience on erosion control for cut-and-fill slopes should be used as a guide.

Figure 4-1 An example of eroded dike slopes.

4.2.3 Animal Protection

If a treatment pond is located in an area that supports burrowing animals, such as muskrats and nutria, design elements can be put in place to control this threat to dike stability. Broken concrete or other riprap that does not completely cover the dike soil can become a home for burrowing animals. Riprap design and placement should emphasize limiting the creation of voids that allow them to burrow near the water surface (Crites et al., 2006).

Varying pond water depth can discourage muskrat infestation (U.S.EPA, 1977b; Crites et al., 2006). Muskrats prefer a partially submerged tunnel, so design provisions to vary the water level over a several-week period will discourage them from burrowing in the dike. Such provisions will often add to the expense of riprap placement for wave protection, but can greatly reduce operation and maintenance expenses.

Figure 4.2 Evidence of burrowing at the edge of a treatment pond (Mayo et al., 2010).

4.2.4 Seepage

Dikes should be designed and constructed to minimize seepage. Vegetation and porous soils should be removed and the embankment should be well compacted. Use of conventional construction equipment is usually suitable for this purpose.

Seepage collars should be provided around any pipes penetrating the dike (Kays, 1986; Thomas et al., 1966). The seepage collars should extend a minimum of 0.6 m from the pipe. Proper installation of transfer pipes can be assured by building up the dike above the pipe elevation, digging a trench for the pipe and seepage collar, backfilling the trench, and compacting the backfill.

In some circumstances it may be necessary to control seepage and ensure bank stability at the exterior toe. A filter blanket material can be used (Middlebrooks, et al. 1978; Kays, 1986). Another method of preventing seepage where embankment material cannot be adequately compacted is placement of an impervious core in the levee with imported material.

4.3 POND SEALING

4.3.1 Introduction

The need for a well-sealed treatment pond has impacted modern pond design, construction, and maintenance, and sealing is required in most design situations. The primary motive for sealing ponds is to prevent seepage. Seepage affects treatment capabilities by causing fluctuation in the water depth and can cause pollution of groundwater. Although many types of pond sealers exist, they can be classified into three major categories: (1) synthetic and rubber liners, (2) earthen and cement liners, and (3) natural and chemical treatment sealers. Within each category there exists a wide variety of application characteristics. Choosing the appropriate lining for a specific site is a critical issue in pond design and seepage control. Detailed information is available from other publications (Kays, 1986; Middlebrooks et al., 1978; USDA, 1997; USDI, 2001, Koerner and Koerner, 2009).

4.3.2 Seepage Rates

Most regulatory agencies limit the amount of seepage from ponds, so it may be important to be able to estimate seepage rates. Stander et al. (1970) presented a summary of information (Table

4.1) on measured seepage rates in wastewater treatment ponds. Seepage rates in irrigation channels can be found in U.S. DI (1991). Seepage is a function of a number of variables; it is difficult to anticipate or predict rates even with extensive soil tests. Careful evaluations must be conducted along with a review of manufacturers' information to determine whether a lining is required and which type. This should be done before the ponds are constructed.

The Minnesota Pollution Control Agency (Hannaman et al., 1978) initiated an intensive study to evaluate the effects of treatment pond seepage from five municipal systems. The five communities were selected for study on the basis of geologic setting, age of the system, and past operating history of the pond. The selected ponds were representative of the major geomorphic regions in the state, and the age of the systems ranged from 3 to 17 years.

Estimates of seepage were calculated by two independent methods for each of the five pond systems. Water balances were calculated by taking the difference between the recorded inflows and outflows, and pond seepage was determined by conducting in-place field permeability tests of the bottom soils at each location. Good correlation was obtained with both techniques.

Table 4-1. Reported Seepage Rates From Pond Systems (from Stander et al., 1970)[a].

Location	**Pond Base**	**Initial Seepage Rate** cm/d ($m^3/m^2/d$)	**Hydraulic Load** $m^3/m^2/d$	**Seepage Rate as percent of Hydraulic Load**	**Settling-in Period**	**Eventual Seepage Rate** cm/d ($m^3/m^2/d$)	**Hydraulic Load** $m^3/m^2/d$	**Seepage Rate as percent of Hydraulic Load**
Mojave[1]	Desert soil (sandy soil)	22.4 (0.19)	0.30	63	9 mo	0.9 (0.007)	0.36	2
Kearney[2b]	Sand and gravel	14.0 (0.12)	0.13	90	1 yr	1.5 (0.013)	0.04	29
Filer City[3]	Sandy soil				Average over 5 yr	0.9 (0.007)	0.009	84
Pretoria[4c]	Clay loam and shale	(0.13)	0.05	Exceeded inflow rate	Approx. 1 yr	0.8 (0.006)	0.05	13

[1]California; [2]Nebraska; [3]Michigan; [4]South Africa
[a]Courtesy of Ann Arbor Science Publishers, Inc., Ann Arbor, MI.
[b]Evaporation and rainfall effects apparently not corrected for. Seepage losses also influenced at times by a high water table.
[c]Constructed in sandy soil for the express purpose of seeping away Paper Mill NSSC liquor.

Field permeability tests indicated that the additional sealing from the sludge blanket was insignificant in locations where impermeable soils were used in the construction process. In the case of more permeable soils, it appeared that the sludge blanket reduced the permeability of the bottom soil from an initial level of 10^{-4} or 10^{-5} cm/sec to the order of 10^{-6} cm/sec. At all five systems evaluated, the treatment pond was in contact with the local groundwater table. Local groundwater fluctuations had a significant impact on seepage rates. Reducing the groundwater gradient resulted in a reduction of seepage losses at three of the sites. Contact with groundwater possibly explains the reduction in seepage rates in many ponds; in the past this reduction in seepage rates has been attributed totally to a sludge buildup. (Stander, et al.)

In an area underlain by permeable material where little groundwater mounding occurs, there is probably little influence from the water table on seepage rates. The buildup of sludge on the bottom of a pond appears to improve the quality of the seepage water leaving the pond. Sludge accumulation apparently increases the cation exchange capacity of the bottom of the pond. Groundwater samples obtained from monitoring wells did not show any appreciable increases in *N*, *P*, or fecal coliform over the background levels after 17 years of operation. The seepage from the ponds did show an increase in soluble salts as great as 20 times over background levels. Concentrations of 25 mg/L to 527 mg/L of chloride were observed.

A comparison of observed seepage rates for various types of liner material is presented in Table 4.2 (Kays, 1986). If an impermeable liner is required, one of the synthetic materials must be used. The East Bay Municipal Utility District, Oakland California, developed the following formula for leakage tolerance, which can be modified by inserting more stringent factors in the denominator, e.g., 100, 200 and so forth. The equation is empirical and its use must be based on experience:

$$Q = \frac{A\sqrt{H}}{80} \tag{4-1}$$

Where:

Q = maximum permissible leakage tolerance, L/min
A = lining area, m^2
H = maximum water depth, m

4.3.3 Natural and Chemical Treatment Sealing

The most complex techniques of pond sealing, either separately or in combination, are natural pond sealing and chemical treatment sealing (Thomas et al., 1966; Bhagat and Proctor, 1969; Seepage Control, Inc., 2005).

Natural sealing of ponds occurs via three mechanisms: (1) physical clogging of soil pores by settled solids; (2) chemical clogging of soil pores by ionic exchange; and (3) biological and organic clogging caused by microbial growth at the pond lining. Which mechanism should be used depends on the characteristics of the wastewater being treated.

Infiltration characteristics of anaerobic ponds were studied in New Zealand (Hill, 1976). Certain soil additives were employed (bentonite, sodium carbonate, sodium triphosphate) in 12 pilot ponds with varying water depth, soil type and compacted bottom soil thickness. It was found that chemical sealing was effective for soils with a minimum clay content of 8 percent and a silt content of 10 percent. Effectiveness increased with clay and silt content.

Four different soil columns were placed at the bottom of an animal wastewater pond to study physical and chemical properties of soil and sealing of ponds (Chang et al., 1974; U.S. DA, 1972). It was discovered that the initial sealing which occurred in the top 5 cm of the soil columns was caused by the trapping of suspended matter in the soil pores. This was followed by a secondary mechanism of microbial growth that completely sealed off the soil from water intrusion.

A similar study performed in Arizona (Wilson et al., 1973) also found this double mechanism of physical and biological sealing. Physical sealing of the pond was enhanced by the use of an organic polymer mixed with bentonite clay. This additive could have been applied with the pond full or empty, although it was more effective when the pond was empty.

Table 4-2. Seepage Rates for Various Liners[a] (Kays, 1986)[b].

Liner Material	Thickness (cm)	Minimum Expected Seepage Rate at 6 m of Water Depth After 1 Yr of Service (cm/d)
Open sand and gravel	NA	244
Loose earth	NA	122
Loose earth plus chemical treatment	NA	30.5
Loose earth plus bentonite	NA	25.4
Earth in cut	NA	30.5
Soil cement (continuously wetted)	10.2	10.2
Gunite	3.8	7.6
Asphalt concrete	10.2	3.8
Un-reinforced concrete	10.2	3.8
Compacted earth	91	0.76
Exposed prefabricated asphalt panels	1.3	0.08
Exposed synthetic membranes	0.11	0.003

NA = not available

[a] The data are based on actual installation experience. The chemical and bentonite treatments

depend on seepage rates, and in the table loose earth values are assumed.
[b]Courtesy of John Wiley & Sons, Inc., New York, NY.

An experiment was performed in South Dakota (Matthew and Harms, 1969) in an effort to relate the sodium adsorption ratio (SAR) of the in situ soil to the sealing mechanism of treatment ponds. The general observation was made that the equilibrium permeability ratio decreases by a factor of 10 as SAR varies from 10 to 80. Polymeric sealants have been used to seal both filled and unfilled ponds (Rosene and Parks, 1973; Seepage Control, Inc., 2005). Unfilled ponds have been sealed by admixing a blend of bentonite and the polymer directly into the soil lining. Filled ponds have been sealed by spraying the fluid surface with alternate slurries of the polymer and bentonite. It has been recommended that the spraying take place in three subsequent layers: (1) polymer, (2) bentonite, and (3) polymer. The efficiency of the sealant has been found to be significantly affected by the characteristics of the impounded water. Most importantly, calcium ions in the water exchange with sodium ions in the bentonite and cause failure of the compacted bentonite linings.

Davis et al., (1973) found that for liquid dairy waste, the biological clogging mechanism predominated. In a San Diego County study site located on sandy loam, the infiltration rate of a virgin pond was measured. A clean water infiltration rate for the pond was 122 cm/d. After two weeks of manure water addition, infiltration averaged 5.8 cm/d; after four months, 0.5 cm/d.

A study performed in southern California (Robinson, 1973) showed similar results. After waste material was placed in the unlined pond in an alluvial silty soil, the seepage rate was reduced. The initial 11.2 cm/d seepage rate dropped to 0.56 cm/d after three months, and to 0.30 cm/d after six months.

4.3.4 Design and Construction Practice

4.3.4.1 Lining Materials

Information about current commercial sources of lining materials is available elsewhere (see Section 4.3.1). Design and construction methods are available from these sources. A general presentation of recommended pond sealing design and construction procedures is presented below. The methods are divided into two categories: (1) bentonite, asphalt, and soil cement liners, and (2) thin membrane liners. Although there are major differences between the two application techniques, there are some similarities between the application of asphalt panels and elastomer liners.

Regardless of the difference between the type of material selected, there are many common design, specification, and construction practices. A summary of the effective design practices in cut-and-fill reservoirs is given below. Most of these practices are common sense observations, yet experience shows that these practices are very often ignored.

Summary of Effective Design Practices for Placing Linings in Cut-and-Fill Reservoirs

- Lining must be placed on a stable soil foundation or structure.

- Facility design and inspection should be the responsibility of professionals with backgrounds in liner applications and experience in geotechnical engineering.

- A continuous underdrain of perforated piping or other configuration to collect groundwater below the lining that operates at atmospheric pressure should be put in place.
- A leakage tolerance should be included in the specifications.
- Continuous, thin, impermeable-type linings should be placed on a smooth surface of concrete, earth, gunite, or asphalt concrete.
- Except for asphalt panels, all field joints should be made perpendicular to the toe of the slope. Some materials can run in any direction, but generally joints run perpendicular to the toe of the slope.
- Formal or informal anchors may be used at the top of the slope.
- Inlet and outlet structures must be sealed properly.
- All lining punctures and cracks in the support structure should be sealed.
- Emergency discharge quick-release devices should be provided in large reservoirs.
- Wind problems with exposed thin membrane liners can be controlled by installing vents so that they are built into the lining.
- Adequate protective fencing must be installed to control vandalism.

Bentonite, Asphalt, and Soil Cement
The application of bentonite, asphalt, and soil cement as lining materials for reservoirs and wastewater ponds has a long history (Kays, 1986). The following summary includes consideration of the materials, costs, evaluations of durability, and effectiveness in limiting seepage. The cost analysis is somewhat arbitrary, since it depends primarily on the availability of the materials. Most states have developed standards relating to the application of these types of materials, and detailed discussions of these materials are presented elsewhere (Middlebrooks et al., 1978; Koerner and Koerner, 2009).

Bentonite
Bentonite is a sodium montmorillonite clay that exhibits a high degree of swelling, imperviousness, and low hydraulic conductivity. The variety of ways in which bentonite may be used to line ponds are listed below:

- A suspension of bentonite in water (with a bentonite concentration of approximately 0.5 percent of the water weight) is placed over the area to be lined. The bentonite settles to the soil surface, forming a thin blanket.
- The same procedure as above, except frequent harrowing of the surface produces a uniform soil-bentonite mixture on the surface of the soil. The amount of bentonite used in this procedure is approximately 4.5 kg/m^2.
- A gravel bed approximately 15 cm deep is first prepared and the bentonite application performed as in the first method. The bentonite will settle through the gravel layer and seal the void spaces.
- Bentonite is spread as a membrane 2.5 - 5 cm thick and covered with a 20 - 30 cm

blanket of soil and gravel to protect the membrane. A mixture of soil and gravel is more satisfactory than soil alone, because the stability is increased and there is greater resistance to erosion.

- Bentonite is mixed with a sand ratio of approximately 1:8. A layer 5 - 10 cm in thickness is placed on the reservoir bottom and covered with a protective cover of sand or soil. This method takes about 13.5 kg/m of bentonite.

In the last two methods listed above, the following construction practices are recommended:

- The section must be over-excavated (30 cm) with drag lines or graders.
- Side slopes should not be steeper than two horizontal to one vertical.
- The sub-grade surface should be dragged to remove large rocks and sharp angles. Usually two passes with adequate equipment are sufficient to smooth the sub-grade.
- Sub-grade should be rolled with a smooth steel roller.
- The sub-grade should be sprinkled to eliminate dust problems. The bentonite or soil-bentonite membrane should then be applied.
- The protective cover should contain sand and small gravel, in addition to cohesive, fine grained material, so that it will be erosion resistant and stable.

The performance of bentonite linings is greatly affected by the quality of the bentonite. Some natural bentonite deposits may contain quantities of sand, silt and clay impurities. Poor quality bentonite deteriorates rapidly in the presence of hard water, and tends to erode in the presence of currents or waves. Bentonite linings must often be put in place manually, which can add considerably to the cost. Wyoming-type bentonite, which is a high-swelling sodium montmorillonite clay, has been found to be satisfactory.

Fine-ground bentonite is generally more suitable for the lining than pit-run bentonite. If the bentonite is finer than a No. 30 sieve, it may be used without specifying size gradation. But if the material is coarser than the No. 30 sieve, it should be well graded. Bentonite should contain a moisture content of less than 20 percent. This is especially important for thin membranes. Some disturbance, and possibly cracking of the membranes, may take place during the first year after construction due to settling of the sub-grade upon saturation. A proper maintenance program, especially at the end of the first year, is a necessity.

Sodium bentonite linings may be effective if they have an adequate amount of exchangeable sodium. Deterioration of the linings has been observed to occur in cases where magnesium or calcium has replaced sodium as the adsorbed ions. A thin layer, less than 15 cm, of bentonite on the soil surface tends to crack if allowed to dry. Because of this, a bentonite soil mixture with a cover of fine grained soil on top, or a thicker bentonite layer, is recommended (Dedrick, 1975). Surface bentonite cannot be expected to be effective longer than two to four years. A buried bentonite blanket may last from 8 to 15 years (U.S. EPA, 1978; U.S. DA, Natural Resources Conservation Services, 2010).

Seepage losses through buried bentonite blankets are approximately 0.2 - 0.25 $m^3/m^2/d$. This figure is for thin blankets and represents about a 60 percent improvement over ponds with no lining.

Asphalt
Asphalt linings may be buried on the surface and may be composed of fresh asphalt or a prefabricated asphalt. Some variations include:

- An asphalt membrane is produced by spraying asphalt at high temperatures. This lining may be either on the surface or buried. Special equipment is needed for installation. A useful life of 18 years or greater has been observed when these membranes are carefully applied and covered with an adequate layer of fine grained soil.
- Buried Asphaltic Membrane. This is similar to the first asphalt membrane, except that a gravel-sand cover is applied over the asphaltic membrane. This cover is usually more expensive and less effective in discouraging plant growth.
- Built-up Linings. These include several different types of materials. One type could be a fiberglass matting, which is applied over a sprayed asphalt layer and then sprayed or swept over with a sealed coat of asphalt or clay. A 280 g jute burlap has also been used as the interior layer between two hot-sprayed asphalt layers. In this case, the total asphalt application should be about 11.3 L/m^2. The prefabricated lining may be on the surface or buried. If it is buried, it could be covered with a layer of soil or, in some cases, a geotextile coating.
- Prefabricated Linings. These linings consist of a fiber or paper material coated with asphalt. This type of liner can be exposed or covered with soil. Joints between the material are sealed with asphaltic mastic. When the asphaltic material is covered, it is more effective and durable. When it is exposed, it should be coated with aluminized paint every three to four years to retard degradation. This is especially necessary above the water line. Joints also have to be maintained if they are not covered with fine-grained soil. Prefabricated asphalt membrane lining is approximately 0.32 - 0.64 cm thick. It may be handled in much the same way as rolled roofing, with lapped and cemented joints. Cover for this material is generally soil and gravel, although shot-crete and macadam may also be used.

Installation procedures for prefabricated asphalt membrane linings and for buried asphalt linings are similar to those for buried bentonite linings (U.S. DI, 2001). The preparation of the sub-grade is important; it should be stable and adequately smooth before the lining is put in place. Linings of bentonite and asphalt are sometimes unsuitable in areas of high weed growth, since weeds and tree roots readily puncture the membranes). Many lining failures occur as a result of rodent and crayfish holes in embankments. Asphalt membrane lining tends to decrease the damage, but, in some cases, harder surface linings are necessary to prevent water loss from embankment failures. Linings of hot applied buried asphalt membrane provide one of the tightest linings available. These linings last longer than other flexible membrane linings. Asphalt linings composed of prefabricated buried materials are best for small jobs, since there is a minimum amount of special equipment and labor connected with installation. For larger jobs sprayed asphalt is more economical. When fibers and filler composed of organic materials are used in building asphalt membranes, the membranes have a shorter lifetime. Inorganic fibers are, therefore, recommended. Typical seepage volume through one buried asphalt membrane after 10 years of service was consistently 0.02 $m^3/m^2/d$ (2.3×10^{-7} cm/s). Asphalt membrane linings can be constructed at any time of the year, but fall and winter installation may dictate the use of the buried asphalt membrane lining.

Buried asphalt membranes usually perform satisfactorily for more than 15 years. When these linings fail, it is generally due to one or more of the following causes:

- Placement of lining on unstable side slopes
- Inadequate protection of the membrane
- Weed growth
- Surface runoff
- Type of sub-grade material
- Cleaning operations
- Scour of cover material Membrane puncture

Soil Cement

The best results are obtained with soil cement when the soil mixed with the cement is sandy and well graded to a maximum thickness of about 2 cm. Soil cement should not be laid down in cold weather. It should be cured for about seven days after placement. Some variations of the soil cement lining are listed below.

- **Standard soil cement** is compacted using a water content of the optimum moisture content of the soil. (Moisture content is expressed in percent dry weight at which a given soil can be compacted to its maximum density by means of a standard method of compaction.) The mixing process is accomplished by traveling mixing machines and can be handled satisfactorily in slopes up to 4:1. Standard soil cement may be on the surface or buried.
- **Plastic soil cement** (surface or buried) is a mixture of soil and cement with a consistency comparable to that of Portland cement concrete. This requires the addition of a considerable amount of water. Plastic soil cement contains from three to six sacks of cement per cubic meter and is approximately 7.5 cm thick.
- **Cement modified soil** contains two to six percent volume of cement. This may be used with plastic fine grained soils. The treatment stabilizes the soil in sections subject to erosion. The lining is constructed by spreading cement on top of loose soil layers by a fertilizer-type spreader. The cement is then mixed with loose soil by a rotary traveling mixer and compacted with a sheeps-foot roller. A 7-day curing period is necessary for a cement modified soil. Soil cement has been used successfully in some cases in mild climates. Where wetting or drying is a factor, or if freezing-thawing cycles are present, the lining will deteriorate rapidly (U.S. DI, 2001).

Thin Membrane Liners

Plastic and elastomeric membranes are popular in applications requiring essentially zero permeability. These materials are economical, resistant to most chemicals if selected and installed properly, available in large sheets simplifying installation, and essentially impermeable. As environmental standards become more stringent, the application of plastic and elastomeric membranes will increase because of the need to guarantee protection against

seepage. This is particularly true for sealing ponds containing toxic wastewaters or the sealing of landfills containing toxic solids.
Most regulatory agencies have general standards for the application of liners, as do most manufacturers. Searching the Internet using key words such as "liners," "plastic liners," "seepage prevention," "sealing," "water proofing," or "membranes" will yield the most current information. Detailed drawings showing the correct method for the application of linings are presented in Kays (1986) and manufacturer's literature. These sources of information should be consulted before designing a liner.

The most difficult design problem encountered in liner application involves placing a liner in an existing pond. Effective design practices are essentially the same as those used in new systems, but the evaluation of the existing structure must be done carefully to achieve the required results. Lining materials must be selected for their compatibility with the existing structure. For example, if a badly cracked concrete lining is to be covered with a flexible synthetic material, it must be properly sealed and the flexible material placed in such a way so that any movement will not destroy the integrity of the new liner. Sealing around existing columns and footings must also be considered.

Protection of a thin membrane lining is essential. Kays (1986) recommends that a fence at least 2 m high be placed on the outside berm slope with the top of the fence below the top elevation of the dike to keep the membrane out of sight.

There are many firms specializing in the installation of lining materials. Most installation companies and manufacturers publish specifications and installation instructions and design details. The manufacturers' and installers' recommendations are similar, but there are differences worthy of consideration when designing a system requiring a liner. For details, consult the Internet for manufacturers using the key words "Pond Liners".

New products are always being developed, and with each new material the options available to designers expand. If the liners are chosen and installed with care, control of seepage and associated pollution should become a minor operation and maintenance element.

4.3.4.2 Mechanisms of Failure

Kays (1986) classified the principal types of failures observed in cut-and-fill reservoirs (Table 4-3). The list is extensive and case histories involving all of the categories are available; however, the most frequently observed failure mechanisms were the lack of integrity in the lining support structure and abuse of the liner. For example, exposed thin membrane liners must be protected from aerator damage, contact with sharp objects, and excess foot traffic. In general, unless a protective cover is provided, it is advisable to use reinforced membranes or thick materials recommended for exposure to the elements.

Table 4-3. Classification of the Principal Failure Mechanisms for Cut-and-Fill Reservoirs (Kays, 1986) [a].

Supporting Structure	Lining
Underdrains	**Mechanical**
Substrate	Field seams
Compaction	Fish moughts[b]
Texture	Structure seals
Voids	Bridging
Subsidence	Porosity
Holes and cracks	Holes and pinholes
Groundwater	Tear strength
Expansive clays	Tensile strength
Out gassing	Extursion and extension
Sloughing	Animals including burrowing birds
Slope anchor stability	Insects
Mud	Weeds
Frozen ground and ice	
	Weather
Operations	General weathering
Cavitation	Wind
Impingement	Wave erosion
Lack of regular cleaning	Ozone
Reverse hydrostatic uplift	
Vandalism	
Seismic activity	

[a]Courtesy of John Wiley and Sons, Inc., New York, NY.
[b]Separation of butyl-type cured sheets at the joint due to unequal tension between the sheets.

4.3.4.3 Cover Material

The cost of linings for ponds vary with the type and the quality required to ensure against seepage problems. Contacting individual suppliers will yield accurate and up-to-date cost information.

Placing cover material over buried membranes is the most expensive part of the procedure. The cover material should, therefore, be as thin as possible, while still providing adequate protection for the membrane. If a significant hydraulic current is present in the pond, the depth of coverage should be greater than 25 cm, and this minimum depth should only be used when the material is erosion resistant and cohesive. Such a material as a clay gravel is suitable. If the material is not cohesive, or if it is fine grained, a higher amount of cover is needed.

Maintenance costs for different types of linings are difficult to estimate. Maintenance should include repair of holes, cracks, and deterioration and damage caused by animals and pond cleaning, as well as weed control expenses. Climate, type of operation, type of terrain, and surface conditions also influence maintenance costs.

Synthetic liners are most practical where zero or minimum seepage regulations are in effect, a facility is treating industrial waste that might degrade concrete or earthen liners and/or there are extremes in climatic conditions

4.4 POND HYDRAULICS

4.4.1 Inlet and Outlet Configuration

In the past, the majority of ponds were designed to receive influent wastewater through a single pipe, usually located toward the center of the pond. Hydraulic and performance studies (Mangelson, 1971; Ewald, 1973; Mangelson and Watters, 1972; Finney and Middlebrooks, 1980; Middlebrooks et al., 1982; Shilton, 2005; Crites et al., 2006) have shown that the use of centralized inlet structures is an inefficient method of introducing wastewater to a pond, often resulting in less than ideal residence time. Multiple inlet arrangements are preferred, even in small ponds (<0.5 ha) and preferably by means of a long splitter box with multiple outlets large enough to avoid plugging by influent solids. The splitter box should be located at approximately mid-depth above the sludge blanket. Outlets should be located as far as possible from the inlets. The inlets and outlets should be placed so that flow through the pond has a uniform velocity profile between the next inlet and outlet.

Single inlets can be used successfully if the inlet is located at the greatest distance possible from the outlet structure and baffled or the flow directed to avoid currents and short circuiting. Outlet structures should be designed for multiple depth withdrawal, and all withdrawals should be a minimum of 0.6 m below the water surface.

4.4.1.1 Pond Transfer Inlets and Outlets

Pond transfer inlets and outlets should be constructed to minimize head loss at peak recirculation rates, assure uniform distribution to all pond areas at all recirculation rates, and maintain water-surface continuity between the supply channel, the ponds, and the return channel. See Section 4.5 for further discussion of recirculation.

Transfer pipes should be numerous and large enough to limit peak head loss to about 7-10 cm with the pipes flowing about two-thirds to three-quarters full. Supply- and return-channel sizing should assure that the total channel loss is no more than one-tenth of the transfer-pipe losses. When such a ratio is maintained, uniform distribution is assured.

By operating with the transfer pipes less than full, unobstructed water surface is maintained between the channels and ponds and scum does not build up in any one area. If the first cell is designed to remove scum, then the transfer pipes must be submerged.

Transfer inlets and outlets usually are made of plastic pipe or bitumastic-coated, corrugated metal pipe, and have seepage collars located near the midpoint. These types of pipe are inexpensive, but strong enough to allow for the differential settlement often encountered in pond-dike construction.

Specially made fiberglass plugs can be provided to close the pipes. The plugs may be installed from a boat. Such plugs permit any pipe to be closed without expensive construction of sluice gates and access platforms at each transfer point. Launching ramps into each pond and channel are recommended to assure easy boat access for sampling, aquatic plant control and pond maintenance.

4.4.2 Baffling

Better treatment is obtained when the flow is guided through the pond. Treatment efficiency, economics and esthetics play an important role in deciding whether or not baffling is desirable. Because there is little horizontal force on baffling except that caused by wave action, the baffle structure need not be particularly strong. The lateral spacing and length of the baffle should be specified so that the cross-sectional area of the flow is as close to a constant as possible.
It may also be placed below the pond surface to help overcome esthetic objections. A typical type of baffle might be a submerged fence attached to posts driven into the pond bottom and covered with a flexible, heavy plastic membrane. Commercial float-supported plastic baffling for ponds also is available.

Baffling has additional advantages. The spiral action induced when flow occurs around the end of the baffles enhances mixing and tends to break up or prevent any stratification or tendency to stratify. Reynolds et al. (1975) and Polprasert and Agarwalla (1995) have discussed the advantages of biomass distribution and attachment to baffles leading to improved pond efficiency. It should be mentioned that winter ice can damage or destroy baffles in cold climates.

4.4.3 Wind Effects

Wind generates a circulatory flow in bodies of water. To minimize short circuiting due to wind, the pond inlet-outlet axis should be aligned perpendicular to the prevailing wind direction. If for some reason the inlet-outlet axis cannot be oriented properly, baffling can be used to control, to some extent, the wind-induced circulation. Where the pond depth is constant, the surface current is in the direction of the wind and the return flow is in the upwind direction along the bottom.

4.4.4 Stratified Ponds

Ponds that are stratified because of temperature differences between the inflow and the pond contents tend to behave differently in winter and summer. In summer, the inflow is generally colder than the pond water. It sinks to the pond bottom and flows toward the outlet. In the winter, the reverse is true. The inflow rises to the surface and flows toward the outlet. A likely consequence of this is that the effective volume of the pond is reduced to that of the stratified inflow layer (density current). The result can be a drastic decrease in detention time and an unacceptable level of treatment.

One strategy is to use selective pond outlets positioned vertically so that outflow is drawn from the layer with density different from that of the inflow. For example, under summer conditions, the inflow will occur along the pond bottom. Hence, the outlets should draw from water near the pond surface.

Another approach is to premix the inflow with pond water while in the pipe or diffuser system, thereby decreasing the density difference. This could be accomplished by regularly constricting the submerged inflow diffuser pipe and locating openings in the pipe at the constrictions. The low pressure at the pipe constrictions would draw in pond water and mix it with the inflow to alter the density. However, in this case, clogging of openings with solid material could be a problem.

4.5 POND RECIRCULATION AND CONFIGURATION

Pond recirculation involves inter- and intra-pond recirculation as opposed to mechanical mixing in the pond cell. The effluents from pond cells are mixed with the influent to the cells. In intra-pond recirculation, effluent from a single cell is returned to the influent to that cell. In inter-pond recirculation, effluent from another pond is returned and mixed with influent to the pond (Figure 4-3).

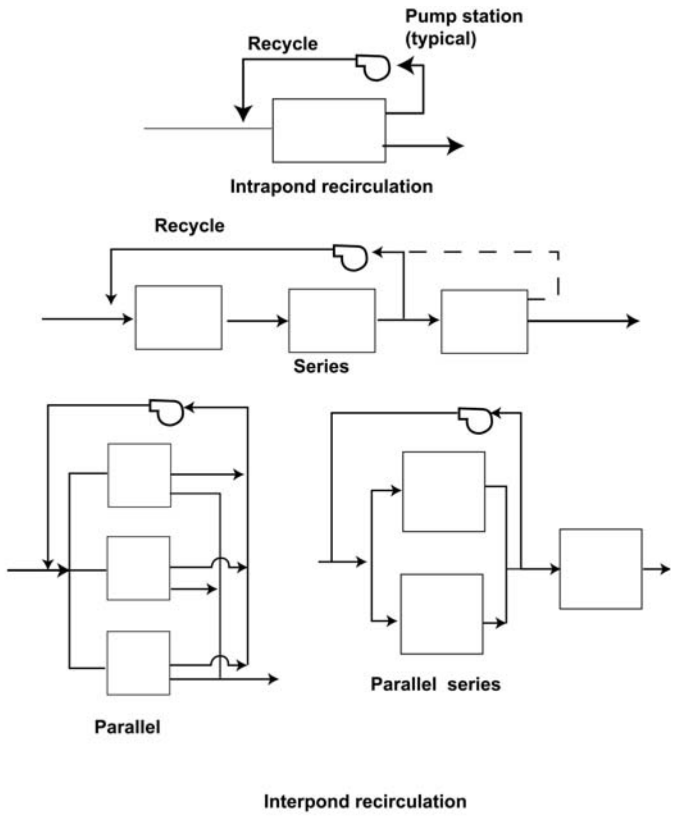

Figure 4-3. Common pond configurations and recirculation systems.

Both methods return active algal cells to the feed area to provide photosynthetic oxygen that can treat some of the organic load. The principal benefit is to control odors and anaerobic conditions in that area of the pond. Inter- and intra-pond recirculation can also affect stratification in ponds. Pond recirculation, however, is not as efficient as mechanical mixing in facultative ponds.

Excessive organic loading of primary ponds and the associated odors can be mitigated by recirculating treated effluent to the overloaded ponds. Recirculation dilutes high BOD_5 concentrations and essentially pushes BOD_5 into downstream ponds, spreading the load over a greater pond surface area in a shorter time than influent flow could do alone. If the recirculated water originates in ponds with high DO, some of this DO mass is brought into the overloaded ponds. However, conventional aeration is likely to be a more energy efficient means of providing DO mass than pumping recirculation water.

Another effect of recirculation is inoculation of primary ponds with microalgae and other organisms from downstream ponds. Inoculation may help maintain algal populations in primary ponds, leading to increased photosynthetic DO and odor control. To promote photosynthesis, water should be recirculated to the surface of the primary ponds in an attempt to form a cap of algae-rich water. Ideally, this recirculated water is warmer than the bulk of the water in the primary ponds. In this way, a surface layer of recirculated water is promoted. However, such a surface cap may be short-lived if night time cooling of the surface allows the surface water to cool and sink. Three common types of inter-pond recirculation systems (series, parallel, and parallel series) are shown in Figure 4-3.

Recirculation in series

Recirculating wastewater through the pond series dilutes the organic mass in the first cell by increasing the flow rate. Neither the mass of material entering the cell nor the surface loading rate (mass/unit area/d) is reduced by this configuration. Intra-cell recirculation does reduce the HRT of the water in the cell receiving the recirculated flow, but not the overall HRT of the system. The method attempts to flush the influent through the pond system faster than it would travel without recirculation, thereby reducing the concentration in the reactor. The reduction in HRT might offset any advantages gained other than odor control. This reduction in the first-pass HRT of the influent and recycled mixture in the first, most heavily loaded, pond in the series system is:

$$t = \frac{V}{(1 + r)Q} \qquad (4\text{-}2)$$

Where:

V = the volume of pond cell
Q = the influent flow rate
r = the recycle flow rate
r/Q = the recycle ratio
t=time

Another effect of recirculation in the series configuration is to reduce the BOD_5 in the mixture entering the pond, and is given by the expression:

$$S_m = \frac{S_{in}}{1 + r} + \left(\frac{r}{1 + r}\right) S_e \qquad (4\text{-}3)$$

Where:

S_m = the BOD_5 of the mixture
S_e = the effluent BOD_5 from the third cell
S_{in} = the influent BOD_5
r = recycle flow rate

S_m would be only 20 percent of S_{in} with a 4:1 recyle ratio, as S_e would be negligible in almost all cases. Thus, the application of organic load in the pond is spread more evenly throughout the ponds, and organic loading and odor generation near the feed points are reduced. Recirculation in series has been used to reduce odors in those cases where the first pond is anaerobic. The recirculation ratio is selected based on the loading rate applied to the cell that will not cause a nuisance.

Recirculation in parallel
The parallel configuration more effectively reduces pond loadings than does the series configuration, because the mixture of influent is spread evenly across all ponds instead of the first pond. For example, consider three ponds, either in series or parallel. In the parallel configuration, the surface loading (kg BOD_5/ha/d) on the three ponds is one-third that of the first pond in the series configuration. The parallel configuration, therefore, is less likely to produce odors than the series configuration. However, the hydraulic improvements in design using a series configuration generally will offset the benefits of reduced loading in parallel configuration.

Based upon the analyses of performance data from selected aerated and facultative ponds, four ponds in series give the best BOD_5 and fecal coliform removals for ponds designed as plug flow systems. Good performance can be obtained with a smaller number of ponds if baffles or dikes are used to optimize the hydraulic characteristics of the system.

Recirculation usually is accomplished with high-volume, low-head propeller pumps. Figure 4-4 presents a simplified cross-section of such an installation. In this design, the cost and maintenance problems associated with large discharge flap gates are eliminated by the siphon discharge. An auxiliary pump with an air eductor maintains the siphon. Siphon breaks are provided to ensure positive backflow protection.

Pumping stations of this type can be designed to maintain full capacity with minimal increase in horsepower even when the inlet and discharge surface levels fluctuate over a range of 1.0 - 1.2 m. Multiple- and/or variable-speed pumps are used to adjust the recirculation rate to seasonal load changes.

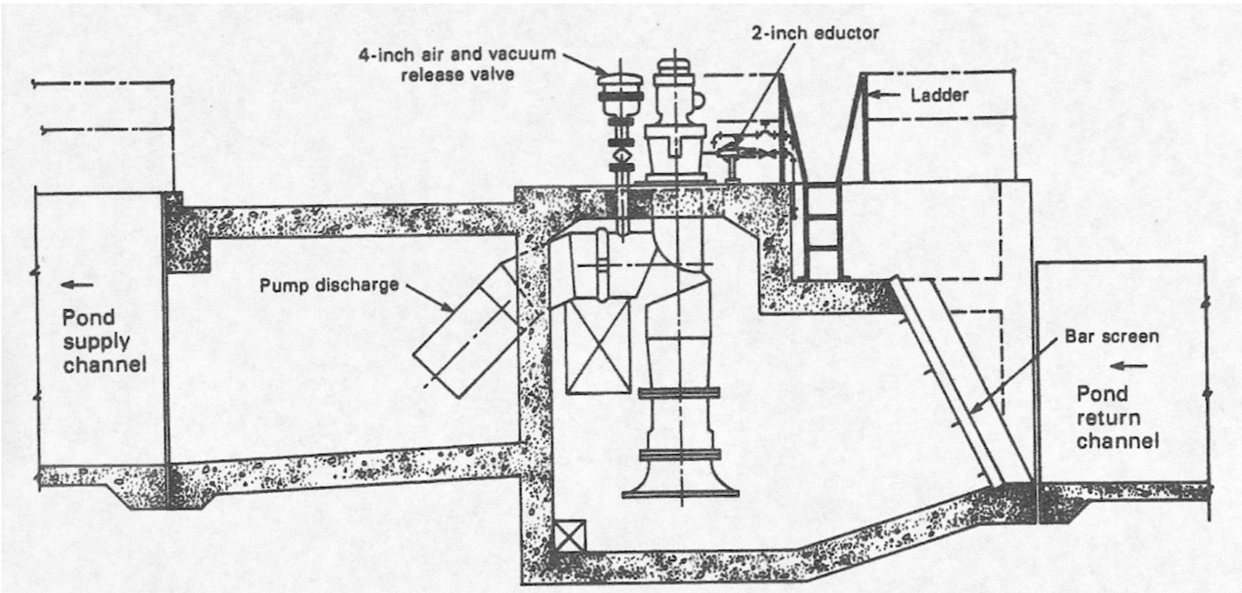

Figure 4-4. Cross-sectional view of a typical recirculation pumping station.

Pond configuration should allow full use of the wetted pond area. Transfer inlets and outlets should be located to eliminate dead spots and short circuiting that may be detrimental to photosynthetic processes. Wind directions should be studied and transfer outlets located to prevent dead pockets where scum will tend to accumulate. Pond size need not be limited, as long as proper distribution is maintained.