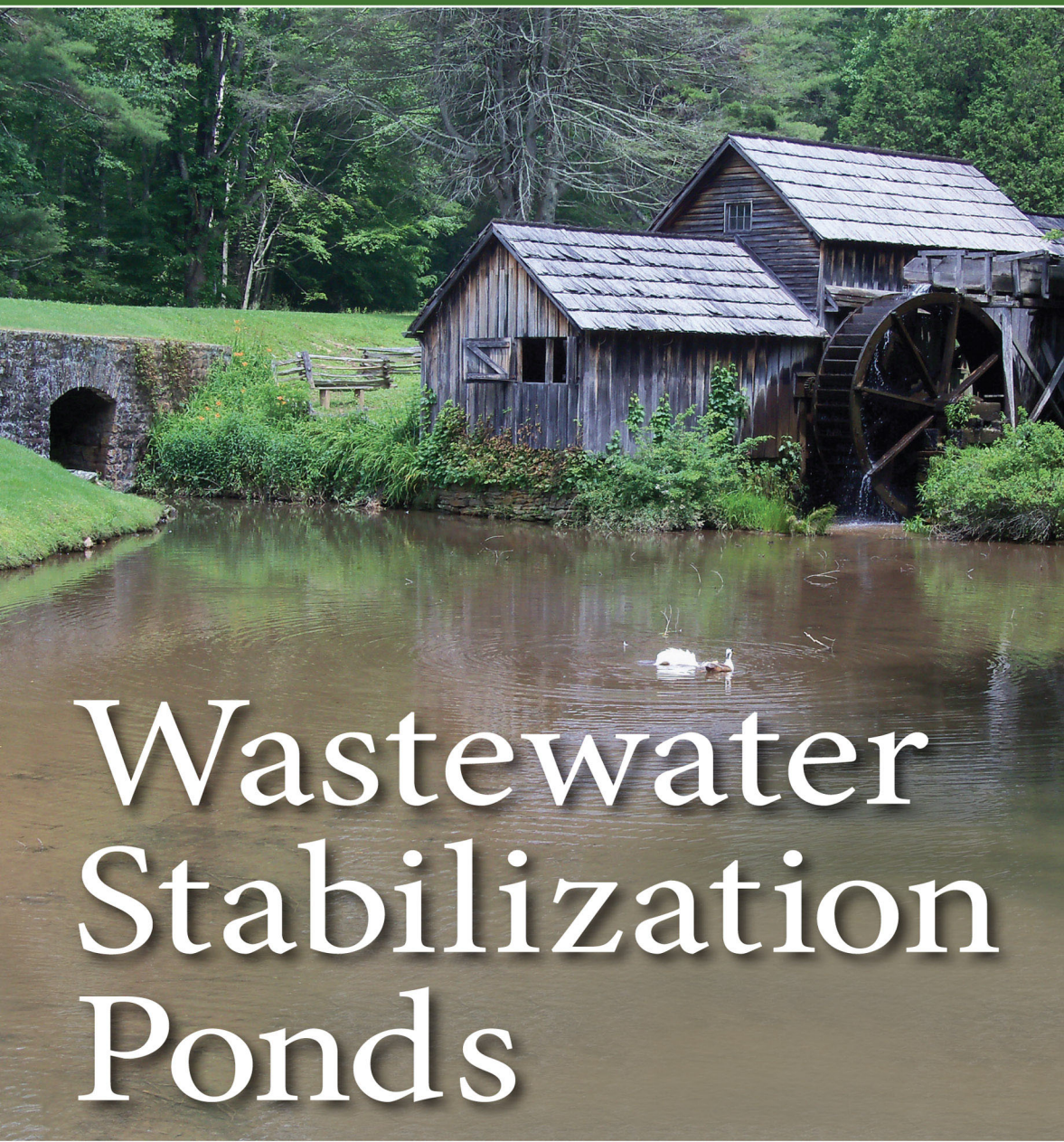




Wastewater Stabilization Ponds

Frank R. Spellman
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CRC Press
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Preface

Wastewater treatment can be accomplished using ponds (lagoons). Ponds are relatively easy to build and manage; they accommodate large fluctuations in flow; and they can provide treatment producing a highly purified effluent that approaches that of conventional systems at much lower cost. It is the cost factor that drives many managers to decide on the pond option. The actual degree of treatment provided depends on the type and number of ponds used. Ponds can be used as the sole treatment or they can be used in conjunction with other forms of wastewater treatment; that is, other treatment unit processes can be followed by a pond or a pond can be followed by other treatment processes.

Stabilization ponds have been used for the treatment of wastewater for over 3000 years. The first recorded construction of a pond system in the United States was at San Antonio, Texas, in 1901. Today, over 8000 wastewater treatment ponds are in place and are being used by more than 50% of the wastewater treatment facilities in the United States. Facultative ponds account for 62%, aerated ponds 25%, anaerobic ponds 0.04%, and total containment ponds 12% of the pond treatment systems. They treat a variety of wastewaters from domestic wastewater to complex industrial wastes, and they function under a wide range of weather conditions, from tropical to arctic. Ponds can be used alone or in combination with other wastewater treatment processes. As our understanding of pond operating mechanisms has increased, different types of ponds have been developed for application in specific types of wastewater under local environmental conditions. This handbook focuses on municipal wastewater treatment pond systems.

The tendency in the United States has been for primarily smaller communities to build ponds; however, in other parts of the world, including Australia, New Zealand, Mexico and Latin America, Asia, and Africa, treatment ponds are being utilized by large cities. Such widespread usage of treatment ponds has added considerably to our understanding of the biological, biochemical, physical, and climatic factors that interact to transform the organic compounds, nutrients, and pathogenic organisms found in sewage into less harmful chemicals and nonviable organisms. A wealth of knowledge has developed as civil, sanitary, or environmental engineers; operators; public works managers; and public health and environmental agencies have gained more experience with these systems. Although some of this information has made its way into technical journals and textbooks, a less formal presentation of the subject would be invaluable for those working in the field every day.

Ponds are designed to enhance the growth of natural ecosystems that are *anaerobic* (providing conditions for bacteria that grow in the absence of oxygen environments), *aerobic* (promoting the growth of oxygen-producing and oxygen-requiring organisms such as algae and bacteria), or *facultative* (a combination of the two). Ponds are managed to reduce concentrations of biochemical oxygen demand, total suspended solids, and coliform numbers (fecal or total) to meet water quality requirements.

This text covers in detail the environmental principles, practices, engineering, and math operations involved in the design and operation of conventional wastewater stabilization ponds. The arrangement of the material lends itself to several different formal course formats. The emphasis of this book is on concepts, definitions, descriptions, and derivations, with a touch of common sense. The major processes, procedures, and design methods relevant to wastewater treatment ponds that are discussed in this book include the basic processes, in-pond design evolution and enhancements, oxygen addition, modifications that require energy, nutrient removal, and effluent total suspended solids removal. This book is intended to be a combination textbook and desk-top reference tool for wastewater practitioners—plant operators, engineers, and managers involved in the protection of water resources.

Authors

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Acronyms and Abbreviations

°C	Degrees Centigrade or Celsius
°F	Degrees Fahrenheit
μ	Micron
μg	Microgram
μm	Micrometer
A/O	Anoxic/oxic
A2/O	Anaerobic/anaerobic/oxic
ac	Acre
ac-ft	Acre-feet
AFP	Advanced facultative pond
AIWP®	Advanced Integrated Wastewater Pond System®
Al ₂ (SO ₄) ₃	Aluminum sulfate (alum)
ANAMMOX	Anaerobic ammonia oxidation
ANSI	American National Standards Institute
AS	Activated sludge
ASCE	American Society of Civil Engineers
ASP	Algae settling pond
atm	Atmosphere
BABE	Bioaugmentation batch enhanced
BAF	Biological aerated filter
BAR	Bioaugmentation reaeration
BASIN	Biofilm activated sludge innovative nitrification
BNR	Biological nutrient removal
BOD	Biochemical oxygen demand
BPR	Biological phosphorus removal
Bti	<i>Bacillus thuringiensis</i>
C	Carbon
CANON	Completely autotrophic nitrogen removal over nitrate
CAPM	Centre for Aquatic Plant Management
CAS	Cyclic activated sludge
CBOD	Carbonaceous biochemical oxygen demand
CFID	Continuous feed international discharge
cfm	Cubic feet per minute
cfs	Cubic feet per second
CH ₄	Methane
CLEAR	Cyclical Pond Extended Aeration Reactor
CO ₂	Carbon dioxide
COD	Chemical oxygen demand
CWSRF	Clean Water State Revolving Fund
DAF	Dissolved air flotation
DAFT	Dissolved air flotation thickening

DMR	Discharge monitoring record
DO	Dissolved oxygen
DON	Dissolved organic nitrogen
EBPR	Enhanced biological phosphorus removal
FeCl ₃	Ferric chloride
FFS	Fixed film system
FWS	Free water surface
gpcd	Gallons per capita per day
gpd	Gallons per day
gpm	Gallons per minute
H ₂ CO ₃	Carbonic acid
H ₂ S	Hydrogen sulfide
H ₂ SO ₄	Sulfuric acid
HCl	Hydrogen chloride
HCO ₃ ⁻	Bicarbonate
HCR	Hydrograph controlled release
hp	Horsepower
HRP	High rate pond
HRT	Hydraulic retention time
I&I	Inflow and infiltration
IPD	In-pond digester
JTU	Jackson turbidity unit
kWh	Kilowatt hour
kWh/yr	Kilowatt-hours per year
MG	Million gallons
MGD	Million gallons per day
mg/L	Milligrams per liter (equivalent to parts per million)
MLSS	Mixed liquor suspended solids
MPN	Most probable number
MSDS	Material Safety Data Sheet
N	Nitrogen
NaOH	Sodium hydroxide (caustic)
NFB	Nitrification filter bed
NH ₃	Ammonia
NH ₄	Ammonium
NO ₂	Nitrite
NO ₃	Nitrate
NPDES	National Pollutant Discharge Elimination System
O&M	Operation and maintenance
OL	Organic load
OP(OR) ₃	Orthophosphate
OSH Act	Occupational Safety and Health Act
PAO	Phosphate-accumulating organism
PEL	Permissible exposure limit
PHA	Polyhydroxyalkanoate
PM	Preventive maintenance

PPE	Personal protective equipment
PO_4^{3-}	Phosphate
POTWs	Publicly owned treatment works
psi	Pounds per square inch
RAS	Return activated sludge
rpm	Revolutions per minute
S	Sulfur
S^0	Elemental sulfur
SAR	Sodium adsorption ratio
SBOD	Soluble biochemical oxygen demand
SBR	Sequencing batch reactor
SDI	Shoreline development index
SF	Subsurface flow
SFP	Secondary facultative pond
SG	Specific gravity
SI	International System of Units
SRT	Solids retention time
TKL	Total Kjeldahl nitrogen
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus
TSS	Total suspended solids
USEPA	U.S. Environmental Protection Agency
UV	Ultraviolet light
VFA	Volatile fatty acid
VSS	Volatile suspended solids
WAS	Waste activated sludge
WWTP	Wastewater treatment plant

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1 Introduction

1.1 SETTING THE STAGE

The primary goals of wastewater treatment ponds focus on simplicity and flexibility of operation, protection of the water environment, and protection of public health. Moreover, ponds are relatively easy to build and manage, they accommodate large fluctuations in flow, and they can also provide treatment that approaches that of conventional systems (producing a highly purified effluent) at much lower cost. It is the cost (the economics) that drives many managers to decide on the pond option of treatment.

Treatment ponds have been employed for the treatment of wastewater for over 3000 years. The first recorded construction of a pond system in the United States was in San Antonio, Texas, in 1901 (Gloyna, 1971). Today, over 8000 wastewater treatment ponds, representing more than 50% of the wastewater treatment facilities in the United States, are in place (USEPA, 2011). Ponds are used to treat wastewater generated by small communities in Europe, and larger pond systems are in place in New Zealand, Australia, and Africa (Mara, 2003). They are used to treat a variety of wastewaters, ranging from domestic to complex industrial effluent, and they function under a wide variety of climatic conditions, from tropical to arctic. Ponds can be used alone or in combination with other wastewater unit treatment processes. As our understanding of pond operating mechanisms has improved, different types of ponds have been developed to meet specific conditions. Ponds generally require less energy than other treatment systems and have lower operational and maintenance costs. It is interesting to note that the basic elements of pond systems have remained unchanged over the past several decades, although aspects of the basic pond designs have evolved and several modifications have been developed in response to increasingly stringent water quality regulatory requirements of point-source (end of the pipe) discharges.

The actual degree of treatment provided in a pond depends on the type and number of ponds in use. Ponds can be the sole type of treatment, or they can be used in conjunction with other forms of wastewater treatment—that is, other treatment processes followed by a pond or a pond followed by other treatment processes. Ponds can be classified based on their location in the system, by the type of wastes they receive, and by the main biological process occurring in the pond. In this chapter, we take a look at the types of ponds according to their location and the type of wastes they receive: raw sewage stabilization ponds, oxidation ponds, and polishing ponds.

1.2 STILL WATERS

Natural freshwater systems may be conveniently considered in two classes: running water or still (standing) water. There is no sharp distinction between the two classes. *Lakes* are defined as basins filled with water with no immediate means of flowing to the sea; they contain relatively still waters. *Ponds* are small lakes in which rooted plants on the top layer reach to the bottom. *Reservoirs* are usually man-made impoundments of potable water. Lakes, ponds, and reservoirs are sensitive to pollution inputs because they flush out their contents relatively slowly. Lakes undergo *eutrophication*, an aging process caused by inputs of organic matter and siltation. Simply put, lakes, ponds, and reservoirs (that is, all still waters) are temporary holding basins.

Wastewater stabilization ponds are also temporary holding basins. When the water has been purified by natural pond processes, it moves on (evaporates) within the water cycle or is pumped or drained from the pond and discharged into downstream unit treatment processes or the receiving body of water. A brief discussion of a natural still water system is included in the following discussion for foundational purposes, to provide a layer of knowledge upon which many layers will be added as we proceed through this text.

1.2.1 NATURAL STILL WATERS

Consider a river pool, isolated by fluvial processes and time from the main stream flow. We are immediately struck by one overwhelming impression: It appears so still ... so very still ... still enough to soothe us. The river pool provides a kind of poetic solemnity, if only at the pool's surface. No words of peace, no description of silence or motionless can convey the perfection of this place, in this moment stolen out of time.

We consider that the water is still, but does the term *still* correctly describe what we are viewing? Is there any other term we can use besides *still*—is there any other kind of still? Yes, of course, we know many ways to characterize still. *Still* can mean inaudible, noiseless, quiet, or silent. *Still* can also mean immobile, inert, motionless, or stationary—which is how the pool appears to the casual visitor on the surface. The visitor sees no more than water and rocks.

The rest of the pool? We know very well that a river pool is more than just a surface. How does the rest of the pool (the subsurface, for example) fit the descriptors we tried to use to characterize its surface? Maybe they fit, maybe they don't. In time, we will go beneath the surface, through the liquid mass, to the very bottom of the pool to find out. For now, remember that images retained from first glances are almost always incorrectly perceived, incorrectly discerned, and never fully understood.

On second look, we see that the fundamental characterization of this particular pool's surface is correct enough. Wedged in a lonely riparian corridor—formed by a river bank on one side and sand bar on the other—between a youthful, vigorous river system on its lower end and a glacier- and artesian-fed lake on its headwater end, almost entirely overhung by mossy old Sitka spruce, the surface of the large pool, at least at this particular location, is indeed still. In the proverbial sense, the pool's surface is as still and as flat as a flawless sheet of glass.

The glass image is a good one, because like perfect glass, the pool's surface is clear, crystalline, unclouded, definitely transparent, and yet perceptively deceptive as well. The water's clarity, accentuated by its bone-chilling coldness, is apparent at close range. Farther back, we see only the world reflected in the water—the depths are hidden and unknown. Quiet and reflective, the polished surface of the water perfectly reflects in mirror-image reversal the spring greens of the forest at the pond's edge, without the slightest ripple. Up close, looking straight into the depths of the pool we are struck by the water's transparency. In the motionless depths, we do not see a deep, slow-moving reach with the muddy bottom typical of a river or stream pool; instead, we clearly see the warm variegated tapestry of blues, greens, and blacks stitched together with threads of fine, warm-colored sand that carpets the bottom, at least 12 feet below. Still waters can run deep.

No sounds emanate from the pool. The motionless, silent water does not, as we might expect, lap against its bank or bubble or gurgle over the gravel at its edge. Here, the river pool, held in temporary bondage, is patient, quiet, waiting, withholding all signs of life from its surface visitor.

Then the reality check: This stillness, like all feelings of calm and serenity, could be fleeting, momentary, temporary, you think. And you would be correct, of course, because there is nothing still about a healthy river pool. At this exact moment, true clarity is present, it just needs to be perceived ... and it will be.

We toss a small stone into the river pool and watch the concentric circles ripple outward as the stone drops through the clear depths to the pool bottom. For a brief instant, we are struck by the obvious: The stone sinks to the bottom, following the laws of gravity, just as the river flows according to those same inexorable laws—downhill in its search for the sea. As we watch, the ripples die away, leaving as little mark as the usual human lifespan creates in the waters of the world, then disappear as if they had never been. Now the river water is as before, still. At the pool's edge, we peer down through the depth to the very bottom—the substrate.

We determine that the pool bottom is not flat or smooth but instead is pitted and mounded occasionally with discontinuities. Gravel mounds alongside small corresponding indentations—small, shallow pits—make it apparent to us that gravel was removed from the indentations and piled into slightly higher mounds. From our top-side position, as we look down through the cool, quiescent liquid, the exact height of the mounds and the depth of the indentations are difficult for us to judge; our vision is distorted through several feet of water. However, we can detect near the low gravel mounds (where female salmon bury their eggs and where their young grow until they are old enough to fend for themselves), and actually through the gravel mounds, movement—water flow—an upwelling of groundwater. This water movement explains our ability to see the variegated color of pebbles. The mud and silt that would normally cover these pebbles have been washed away by the water's subtle, inescapable movement. Obviously, in the depths, our still water is not as still as it first appeared.

The slow, steady, inexorable flow of water in and out of the pool, along with the upflowing of groundwater through the pool's substrate and through the salmon redds (nests) is only a small part of the activities occurring within the pool, including the air above it, the vegetation surrounding it, and the damp bank and sandbar forming its sides.

Let's get back to the pool itself. If we could look at a cross-sectional slice of the pool, at the water column, the surface of the pool may carry those animals that can literally walk on water. The body of the pool may carry rotifers and protozoans and bacteria—tiny microscopic animals—as well as many fish. Fish will also inhabit hidden areas beneath large rocks and ledges, to escape predators. Going down further in the water column, we come to the pool bed. This is the benthic zone, and certainly the greatest number of creatures live here, including larvae and nymphs of all sorts, worms, leeches, flatworms, clams, crayfish, dace, brook lampreys, sculpins, suckers, and water mites.

We need to go down even farther, down into the pool bed, to see the whole story. How far we have to go and what lives here, beneath the water, depends on whether it is a gravelly bed or a silty or muddy one. Gravel will allow water, with its oxygen and food, to reach organisms that live underneath the pool. Many of the organisms that are found in the benthic zone may also be found underneath, in the hyporheic zone.

But to see the rest of the story we need to look at the pool's outlet, where its flow enters the main river. This is a riffle area—a shallow place where water runs fast and is disturbed by rocks. Only organisms that cling very well, such as net-winged midges, caddisflies, stoneflies, some mayflies, dace, and sculpins can spend much time here, and the plant life is restricted to diatoms and small algae. Riffles are a good place for mayflies, stoneflies, and caddisflies to live because they offer plenty of gravel to hide in.

Earlier, we struggled to find the right words to describe the river pool. Eventually, we settled on *still waters*. We did this because of our initial impression, and because of our lack of understanding and lack of knowledge. Even knowing what we know now, we might still describe the river pool as still waters. However, in reality, we must call the pool what it really is—a dynamic habitat. Each river pool has its own biological community, the members interwoven with each other in complex fashion, all depending on each other. Thus, our river pool habitat is part of a complex, dynamic ecosystem. On reflection, we realize, moreover, that anything dynamic certainly cannot be accurately characterized as still—including our river pool (Spellman, 2007).

1.3 411 ON PONDS

Wastewater stabilization ponds are designed to enhance natural still water ponds and take them to an advanced level of operation and function. They can be *anaerobic* (provide conditions for bacteria that grow in the absence of oxygen environments), *aerobic* (promote the growth of organisms that produce or require oxygen, such as algae and bacteria), or *facultative* (a combination of the two). Historically, the main purpose of ponds has been to provide detention time for wastewater to allow it to be stabilized through natural processes. Ponds are managed to reduce concentrations of biochemical oxygen demand (BOD), total suspended solids (TSS), and coliform numbers (fecal or total) to meet water quality requirements. Table 1.1 summarizes information on pond applications, loading, and size of wastewater treatment ponds. When properly designed and operated, ponds are capable of providing the equivalent of secondary treatment for both BOD and suspended solids.

TABLE 1.1
Basic Wastewater Pond Specifications

Pond	Application	Typical Loading ^a (kg/1000 m ² /d)	Typical Detention Time (d)	Typical Depth (m)	Comments
Anaerobic	Industrial wastewater	280–4500	5–50	2.5–4.5	Subsequent treatment normally required
Aerobic	Generally used to treat effluent from other processes; produces effluent low in soluble BOD ₅ and high in algal solids	112–225	2–6	0.18–0.3	Maximizes algae production and, if algae are harvested, nutrient removal
Facultative	Raw municipal wastewater; effluent from primary treatment, trickling filters, aerated ponds, or anaerobic ponds	22–56	7–50	0.9–2.4	Most common wastewater treatment pond; may be aerobic through entire depth if lightly loaded

Sources: Adapted from Curi, K. and Eckenfelder, Jr., W.W., *Theory and Practice of Biological Wastewater Treatment*, Springer, New York, 1980; Spellman, F.R., *Handbook of Water and Wastewater Treatment Plant Operations*, 3rd ed., CRC Press, Boca Raton, FL, 2013.

^a BOD₅, biochemical oxygen demand, measured over 5 days.

In comparison to biomechanical wastewater treatment systems, ponds have advantages and disadvantages. The advantages include the following:

- Low construction cost
- Low operational cost
- Low energy usage
- Can accept surge loadings
- Low chemical usage
- Fewer mechanical problems
- Easy operation
- No continuous biosolids handling

The disadvantages include the following:

- Large land requirements
- Possible groundwater contamination from leakage
- Treatment affected by climatic conditions
- Possible suspended solids problems (algae)

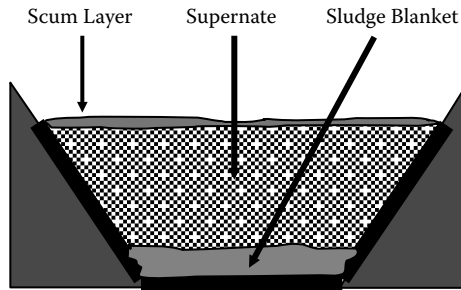


FIGURE 1.1 Anaerobic pond.

- Possible spring odor
- Animal problems (muskrats, turtles, etc.)
- Vegetation problems (rooted weeds, duckweed, algae)
- Localized sludge problems (deposition near inlet)

1.3.1 ANAEROBIC PONDS

Anaerobic ponds receive such a heavy organic loading that they have no aerobic zone. They are usually 2.5 to 4.5 m (8.2 to 14.8 ft) in depth and have detention times of 5 to 50 days (see Figure 1.1). The predominant biological treatment reactions are bacterial acid formation and methane fermentation. Anaerobic ponds work like a septic tank.

1.3.1.1 Process Description

In anaerobic ponds, acid-producing bacteria convert organic matter to volatile acids, carbon dioxide, water, and nitrogen. Methane-fermenting bacteria break down acids and other products to methane gas, carbon dioxide, hydrogen sulfide, alkalinity, and water. Anaerobic ponds are usually used for special applications such as treatment of strong industrial and agricultural wastes (e.g., from food processing such as meat packing and slaughter houses), as a pretreatment step in municipal systems, or where an industry is a significant contributor to a municipal system. The biochemical reactions in an anaerobic pond produce hydrogen sulfide (H_2S) and other odorous compounds. To reduce odors, the common practice is to recirculate water from a downstream facultative or aerated pond. This provides a thin aerobic layer at the surface of the anaerobic pond, which prevents odors from escaping into the air. A cover may also be used to contain odors. The effluent from anaerobic ponds usually requires further treatment prior to discharge.

1.3.2 AEROBIC PONDS

Aerobic ponds, also known as *oxidation ponds* or *high-rate aerobic ponds*, maintain dissolved oxygen (DO) throughout their entire depth. They are usually 30 to 45 cm (0.9 ft to 1.5 ft) deep, which allows light to penetrate throughout the pond.

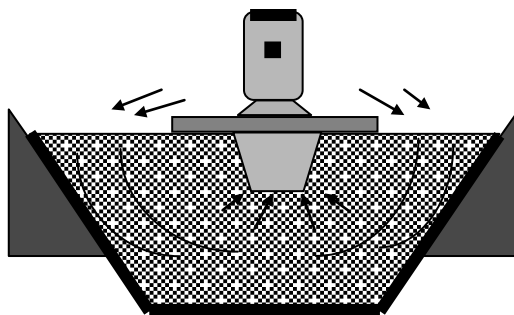


FIGURE 1.2 Aerobic pond.

Mixing is often provided via mechanical aeration (see Figure 1.2) to keep algae at the surface to maintain maximum rates of photosynthesis and oxygen production and to prevent algae from settling and producing an anaerobic bottom layer. The rate of photosynthetic production of oxygen may be enhanced by surface reaeration; oxygen and aerobic bacteria biochemically stabilize the waste. Detention time is typically 2 to 6 days.

1.3.2.1 Process Description

Aerobic ponds rely on algae consuming carbon dioxide, nutrients, and inorganic salts (ammonia), using sunlight as a source of energy. Oxygen is produced as a waste product. This process is known as *photosynthesis*. As algae and bacteria cells die off, they are then used as an organic food source by the bacteria. Aerobic bacteria utilize free dissolved oxygen to break down organics and nutrients for food, and they release water, carbon dioxide, and ammonia as wastes. This process is known as *respiration*.

These ponds are appropriate for treatment in warm, sunny climates. They are used where a high degree of BOD₅ removal is desired but land area is limited. The chief advantage of these ponds is that they produce a stable effluent during short detention times with low land and energy requirements. However, their operation is somewhat more complex than that of facultative ponds, and, unless the algae are removed, the effluent will contain high TSS. Although the shallow depths allow penetration of ultraviolet (UV) light, which may reduce pathogens, shorter detention times may work against effective coliform and parasite die-off. Because such ponds are shallow, bottom paving or veering is usually necessary to prevent aquatic plants from colonizing them. The Advanced Integrated Wastewater Pond System® (AIWPS®) utilizes a high-rate pond to maximize the growth of microalgae through the use of a low-energy paddle-wheel. This use of high-rate ponds will be discussed later in the text.

1.3.3 FACULTATIVE PONDS

The most common type of pond for municipal waste is the facultative pond, which may also be called an *oxidation* or *photosynthetic pond*. Facultative ponds are usually 0.9 to 2.4 m (2.9 to 7.8 ft) deep or deeper, with an aerobic layer overlying an

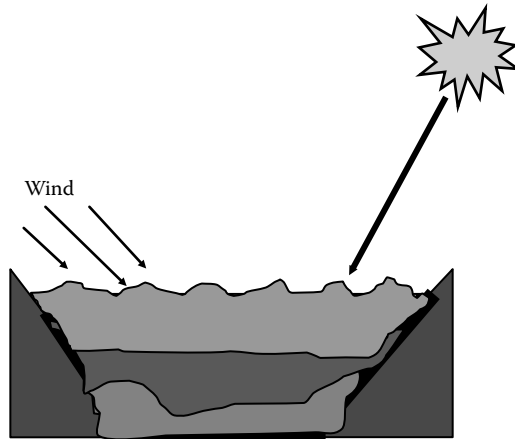


FIGURE 1.3 Facultative pond.

anaerobic layer. Recommended detention times vary between 5 to 50 days in warm climates and 90 to 180 days in colder climates (NEIWPCC, 1998). Aerobic treatment processes in the upper layer provide odor control and nutrient and BOD removal. Anaerobic fermentation processes, such as sludge digestion, denitrification, and some BOD removal, occur in the lower layer. The keys to successful operation of this type of pond are oxygen production by photosynthetic algae and wind action reaeration at the surface (see Figure 1.3).

Facultative ponds are used to treat raw municipal wastewater in small communities and for primary or secondary effluent treatment for small or large cities. They are also used in industrial applications, usually in the process line after aerated or anaerobic ponds, to provide additional treatment prior to discharge. Commonly achieved effluent BOD values, as measured in the BOD₅ test, range from 20 to 60 mg/L, and TSS levels may range from 30 to 150 mg/L. The size of the pond necessary to treat BOD loadings depends on specific conditions and regulatory requirements.

Facultative ponds overloaded due to unplanned additional sewage volume or higher strength influent from a new industrial connection may be modified by the addition of mechanical aeration. Ponds originally designed for mechanical aeration are generally 2 to 6 m (6.6 to 19.7 ft) deep with detention times of 3 to 10 days; for colder climates, 20 to 40 days may be required (NEIWPCC, 1998). Mechanically aerated ponds require less land area but have greater energy requirements.

DID YOU KNOW?

Facultative organisms can use either dissolved oxygen or combined oxygen, because they can adapt to changing conditions. They can continue decomposition when the system changes from aerobic or anaerobic or from anaerobic to aerobic.

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2 Pond Process Elements

2.1 MICROORGANISMS

Microorganisms are significant in wastewater because of their role in disease transmission, and they are the primary agents of biological treatment. Thus, wastewater practitioners must have considerable knowledge of the microbiological characteristics of wastewater and wastewater stabilization ponds. Simply, wastewater operators must know the principal groups of microorganisms found in wastewater as well as those that must be treated (pathogenic organisms), removed, or controlled using biological treatment processes. They must be able to identify the organisms that serve as indicators of pollution and know their significance, and they must be familiar with the methods used to enumerate the indicator organisms. This chapter provides microbiology fundamentals specifically targeting the needs of wastewater specialists involved in the operation of wastewater stabilization ponds.

Note: To have microbiological activity the body of wastewater must possess the appropriate environmental conditions. The majority of wastewater treatment processes, for example, are designed to operate using an aerobic process. The conditions required for aerobic operation are (1) sufficient free, elemental oxygen; (2) sufficient organic matter (food); (3) sufficient water; (4) enough nitrogen and phosphorus (nutrients) to permit oxidation of the available carbon materials; (5) proper pH (6.5 to 9.0); and (6) lack of toxic materials.

2.2 MICROBIOLOGY: WHAT IS IT?

Biology is generally defined as the study of living organisms (i.e., the study of life). Microbiology is a branch of biology that deals with the study of microorganisms so small in size that they must be studied under a microscope. Microorganisms of interest to wastewater operators include bacteria, protozoans, viruses, and algae, among others. Wastewater operators have the same microbiological concerns as water operators, but instead of directly purifying water for consumer consumption the focus of wastewater operators is on removing harmful pathogens from the wastestream before outfalling it to the environment.

Note: The science and study of bacteria are known as *bacteriology*.

2.3 WASTEWATER MICROORGANISMS

Microorganisms of interest to wastewater operators include bacteria, protozoans, viruses, algae, rotifers, fungi, and nematodes. These organisms are the most diverse group of living organisms on Earth, and they occupy important niches in

the ecosystem. Their simplicity and minimal survival requirements allow them to exist in diverse situations. Because *waterborne diseases* are a major health concern, water treatment specialists are mostly concerned with how to control the *waterborne pathogens* (e.g., bacteria, virus, protozoans) that cause them. The focus of wastewater operators, on the other hand, is on the millions of organisms that arrive at the stabilization pond with the influent. The majority of these organisms are nonpathogenic and are beneficial to pond operations. From a microbiological standpoint, the predominant species of microorganisms depend on the characteristics of the influent, environmental conditions, process design, and mode of pond operation. Pathogenic organisms, however, may be present. These include the organisms responsible for diseases such as typhoid, tetanus, hepatitis, dysentery, gastroenteritis, and others.

To understand how to minimize or maximize the growth of microorganisms and control pathogens one must study the structure and characteristics of the microorganisms. In the sections that follow, we will look at the major groups of microorganisms that are important to wastewater operators and discuss their size, shape, nutritional needs, and control.

Note: In a water environment, water is not a medium for the growth of microorganisms but is instead a means of transmission; that is, it serves as a conduit, thus the term *waterborne*. Disease outbreaks occur when individuals consume water carrying pathogens. When the topic of waterborne disease is brought up, we might mistakenly assume that waterborne pathogens are at home in water, but nothing could be further from the truth. A water-filled environment is not where a pathogenic organism would choose to live, if it had such a choice. Microorganisms do not normally grow, reproduce, and thrive in watery surroundings. Pathogenic microorganisms temporarily residing in water are simply biding their time, going with the flow, waiting for their opportunity to meet up with their unsuspecting host or hosts. When the pathogenic microorganism finds its host, it is finally home ... or it may have found its final resting place (Spellman, 1997).

2.4 KEY TERMS

To converse with the reader in an understandable way it is important to abide by the sage words of Voltaire: “If you wish to converse with me, please define your terms.”

Acre-foot—A volume of liquid in one surface acre (43,560 square feet) $\times$ 1 foot deep (43,560 cubic feet).

Aerobic—A condition in which free dissolved oxygen is available in the aquatic environment.

Aerobic bacteria—Bacteria that require free dissolved oxygen for growth.

Algae, simple—Plants, many microscopic, that contain chlorophyll. Freshwater algae are diverse in shape, color, size, and habitat. They are the basic link in the conversion of inorganic constituents in water into organic constituents.

Algal bloom—Sudden spurts of algal growth that can affect water quality adversely and indicate potentially hazardous changes in local water chemistry.

Algicide—Any substance or chemical used to kill or control algae growth.

Anaerobic—Able to live and grow in the absence of free oxygen.

Anaerobic decomposition—The breakdown of organic compounds by bacteria in the absence of dissolved oxygen.

Autotrophic organisms—Organisms that produce food from inorganic substances.

Bacteria—Single-celled microorganisms that possess rigid cell walls. They may be aerobic, anaerobic, or facultative. They can cause disease, but some are important in pollution control.

Biochemical oxygen demand (BOD)—The rate at which organisms use oxygen to stabilize decomposable organic matter. BOD measurements are used to determine the organic strength of wastewater.

Biogeochemical cycle—The chemical interactions occurring among the atmosphere, hydrosphere, and biosphere.

Coliform organism—Microorganisms found in the intestinal tract of humans and animals. Their presence in water indicates fecal pollution and potentially adverse contamination by pathogens.

Denitrification—Anaerobic biological reduction of nitrate to nitrogen gas.

Dissolved oxygen—Molecular oxygen dissolved in a liquid.

Facultative bacteria—Bacteria that can adapt to either aerobic or anaerobic conditions.

Fungi—Simple plants lacking the ability to produce energy through photosynthesis.

Heterotrophic organisms—Organisms that are dependent on organic matter for food.

Hydraulic loading—Volume of flow per unit area.

Organic loading—Number of pounds of BOD added per unit area.

Population equivalent—Population that would contribute the same amount of BOD as the wastewater.

Photosynthesis—Process in which plants produce living organic material from carbon dioxide, water, and inorganic salts by using sunlight as the source of energy. Oxygen is produced in this process as a waste.

Prokaryotic cell—Simple cell type characterized by the lack of a nuclear membrane and the absence of mitochondria.

Short-circuiting—Condition in which some of the water flows faster than the rest of the water through a tank or basin.

Virus—Smallest form of microorganisms capable of causing disease.

2.5 BACTERIA

The simplest wholly contained life systems are bacteria (*prokaryotes*), which are the most diverse group of microorganisms. Among the most common microorganisms in water, they are primitive, unicellular (single-celled) organisms possessing no well-defined nucleus. They come in a variety of shapes and nutritional needs. Bacteria contain about 85% water and 15% ash or mineral matter. The ash is largely composed of sulfur, potassium, sodium, calcium, and chlorides, with small amounts of iron, silicon, and magnesium. Bacteria reproduce by binary fission.

TABLE 2.1
Forms of Bacteria

Form	Technical Name		Example
	Singular	Plural	
Sphere	Coccus	Cocci	<i>Streptococcus</i>
Rod	Bacillus	Bacilli	<i>Bacillus typhosis</i>
Curved or spiral	Spirillum	Spirilla	<i>Spirillum cholera</i>

Note: Binary fission occurs when one organism splits or divides into two or more new organisms.

Bacteria, once considered the smallest living organisms (now it is known that smaller forms of matter exhibit many of the characteristics of life), range in size from 0.5 to 2 microns in diameter and about 1 to 10 microns long.

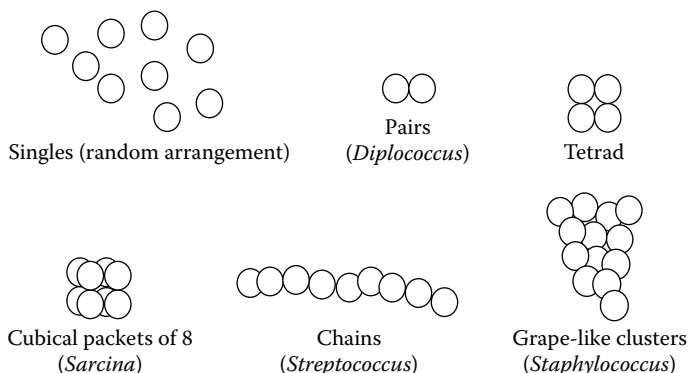
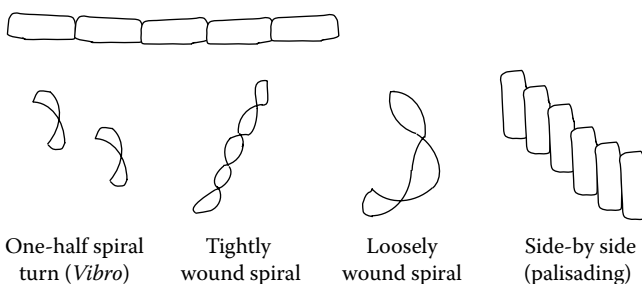
Note: A *micron* is a metric unit of measurement equal to 1 thousandth of a millimeter. To visualize the size of bacteria, consider that about 1000 bacteria lying side by side would reach across the head of a straight pin.

Bacteria are categorized into three general groups based on their physical form or shape (although almost every variation has been found; see Table 2.1). The simplest form is the sphere. Spherical-shaped bacteria are called *cocci* (“berries”). They are not necessarily perfectly round, but may be somewhat elongated, flattened on one side, or oval. Rod-shaped bacteria are called *bacilli*, and spiral-shaped bacteria are called *spirilla*. Spirilla have one or more twists and are never straight (see Figure 2.1). Such formations are usually characteristic of a particular genus or species. Within these three groups are many different arrangements. Some exist as single cells, whereas others exist as pairs, packets of four or eight, chains, or clumps.

Most bacteria require organic food to survive and multiply. Plant and animal material that gets into the water provides the food source for bacteria. Bacteria convert the food to energy and use the energy to make new cells. Some bacteria can survive and multiply using inorganics (e.g., minerals such as iron) as an energy source when organics (pollution) are not available.

Several factors affect the rate at which bacteria grow, including temperature, pH, and oxygen levels. The warmer the environment, the faster the rate of growth. Generally, for each increase of 10°C, the growth rate doubles, but heat can also be used to kill bacteria. Most bacteria grow best at neutral pH. Extreme acidic or basic conditions generally inhibit growth, although some bacteria may require acidic conditions and some alkaline conditions for growth.

Again, bacteria are aerobic, anaerobic, or facultative. Aerobic bacteria require free oxygen in the aquatic environment. Anaerobic bacteria exist and multiply in environments that lack dissolved oxygen. Facultative bacteria (e.g., iron bacteria) can switch from aerobic growth to anaerobic growth; that is, they can grow in both anaerobic or aerobic environments.

Cocci (spherical shapes)**Bacilli (cylindrical or rod-shaped)****FIGURE 2.1** Bacterial shapes and arrangements.

Under optimum conditions, bacteria grow and reproduce very rapidly by binary fission. An important point to consider in connection with bacterial reproduction is the rate at which the process can take place. The total time required for an organism to reproduce and the offspring to reach maturity is the *generation time*. Bacteria growing under optimal conditions can double their number about every 20 to 30 minutes. Obviously, this generation time is very short compared with that of higher plants and animals. Bacteria continue to grow at this rapid rate as long as nutrients hold out—even the smallest contamination can result in a sizable growth in a very short time.

Note: Even though wastewater can contain bacteria counts in the millions per milliliter, in wastewater treatment, under controlled conditions, bacteria can help to destroy and to identify pollutants. In such processes, bacteria stabilize organic matter (e.g., activated sludge processes) and thereby assist the treatment process in producing effluent that does not impose an excessive oxygen demand on the receiving body. Coliform bacteria can be used as an indicator of pollution by human or animal wastes.

Several types of bacteria can be found in the pond; these organisms help to decompose complex, organic constituents in the influent to simple, nontoxic compounds. Certain pathogenic bacteria and other microbial organisms (viruses, protozoans) that are associated with human waste enter into the system with the influent, but the wastewater treatment process is designed to reduce their numbers enough to meet public health standards. Their fate in wastewater ponds will be discussed later.

2.5.1 AEROBIC BACTERIA

Bacteria found in the aerobic zone of a wastewater pond are primarily the same type as those found in an activated sludge process or in the zoogeal mass of a trickling filter. The most frequently isolated bacteria include *Beggiatoa alba*, *Sphaerotilus natans*, *Achromobacter*, *Alcaligenes*, *Flavobacterium*, *Pseudomonas*, and *Zoogoea* spp. (Lynch and Poole, 1979; Pearson, 2005). These organisms decompose the organic materials present in the aerobic zone into oxidized end products.

2.5.2 ANAEROBIC BACTERIA

Hydrolytic bacteria convert complex organic material into simple alcohols and acids, primarily amino acids, glucose, fatty acids, and glycerols (Brockett, 1976; Paterson and Curtis, 2005; Pearson, 2005). Acidogenic bacteria convert the sugars and amino acids into propionic, acetic, and butyric acids. Acetogenic bacteria convert these organic acids into acetate, ammonia (NH_3), hydrogen (H), and carbon dioxide (CO_2). Methanogenic bacteria break down these products further to methane (CH_4) and CO_2 (Gallert and Winter, 2005).

2.5.3 CYANOBACTERIA

Cyanobacteria, formerly classified as blue-green algae, are autotrophic organisms that are able to synthesize organic compounds using CO_2 as the major carbon source. Cyanobacteria produce oxygen (O_2) as a byproduct of photosynthesis, providing an O_2 source for other organisms in the ponds. They are found in very large numbers as blooms when environmental conditions are suitable (Gaudy and Gaudy, 1980). Commonly encountered cyanobacteria include *Oscillatoria*, *Arthrospira*, *Spirulina*, and *Microcystis* (Vasconcelos and Pereira, 2001).

2.5.4 PURPLE SULFUR BACTERIA

Purple sulfur bacteria (Chromatiaceae) may grow in any aquatic environment to which light of the required wavelength penetrates, provided that CO_2 , nitrogen (N), and a reduced form of sulfur (S) or H are available. Purple sulfur bacteria occupy the anaerobic layer below the algae, cyanobacteria, and other aerobic bacteria in a pond. They are commonly found at a specific depth, in a thin layer where light and nutrient conditions are at an optimum (Gaudy and Gaudy, 1980; Pearson, 2005). Their biochemical conversion of odorous sulfide compounds to elemental sulfur or sulfate (SO_4) helps to control odor in facultative and anaerobic ponds.

2.6 ALGAE

You do not have to be a wastewater operator to understand that algae can be a nuisance. Many ponds and lakes in the United States are currently undergoing *eutrophication*, enrichment of an environment with inorganic substances (e.g., phosphorus and nitrogen) that causes excessive algae growth and premature aging of the water body. The average person may not know what eutrophication means; however, when eutrophication occurs, especially when filamentous algae such as *Caldophora* break loose in a pond or lake and wash ashore, algae makes its stinking, noxious presence known.

Not all the news about algae is bad, however. Algae and bacteria are essential for proper functioning of a treatment pond. This relationship will be explained in more detail later, but for now it is important to provide a few basic facts about algae. Algae are a group of aquatic organisms that may be unicellular or multicellular, motile or immotile. Also, depending on the phylogenetic family, they have different combinations of photosynthetic pigment. These pigment differences are used to classify the aquatic plants (e.g., green algae, blue-green algae, golden-brown algae). As autotrophs, algae need only inorganic nutrients, such as nitrogen, phosphorus (P), and a suite of microelements, to fix CO_2 and grow in the presence of sunlight. Algae do not fix atmospheric nitrogen; they require an external source of inorganic nitrogen in the form of nitrate (NO_3^-) or NH_3 . Some algal species are able to use amino acids and other organic nitrogen compounds. Oxygen is a byproduct of these reactions.

Algae come in many shapes and sizes (see Figure 2.2). Although they are not pathogenic, algae do cause problems with wastewater treatment plant operations. They grow easily on the walls of troughs and basins, and heavy growth can plug intakes and screens. Additionally, some algae release chemicals that give off undesirable tastes and odors. Algae are usually classified by their color and are generally divided into three groups, based on the color reflected from the cells by the chlorophyll and other pigments involved in photosynthesis. Green and brown algae are common to wastewater ponds; red algae occur infrequently. The algal species that is dominant at any particular time is thought to be primarily a function of temperature, although the effects of predation, nutrient availability, and toxins are also important.

Green algae (Chlorophyta) include unicellular, filamentous, and colonial forms. Some green algal genera commonly found in facultative and aerobic ponds are *Euglena*, *Phacus*, *Chlamydomonas*, *Ankistrodesmus*, *Chlorella*, *Micractinium*,

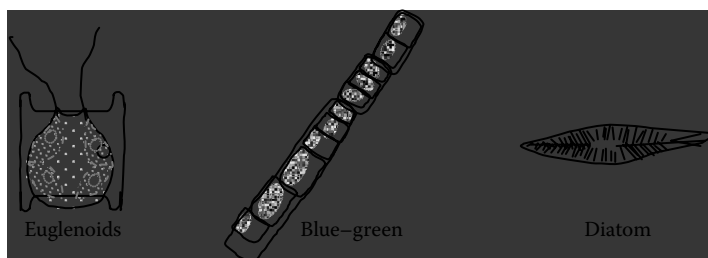


FIGURE 2.2 Algae.

Scenedesmus, *Selenastrum*, *Dictyosphaerium*, and *Volvox*. Chrysophytes, or brown algae, are unicellular and may be flagellated; they include the diatoms. Certain brown algae are responsible for toxic and red blooms. Brown algae found in wastewater ponds include the diatoms *Navicula* and *Cyclotella*. Red algae (Rhodophyta) include a few unicellular forms but are primarily filamentous (Gaudy and Gaudy, 1980; Pearson, 2005).

Algae, however, are also commonly classified based on their cellular properties or characteristics. Characteristics used to classify algae include (1) cellular organization and cell wall structure; (2) the nature of the chlorophylls; (3) the type of motility, if any; (4) the carbon polymers that are produced and stored; and (5) the reproductive structures and methods.

Many algae (in mass) are easily seen by the naked eye; others are microscopic. They occur in fresh and polluted water, as well as in saltwater. Because they are plants, they are capable of using energy from the sun for photosynthesis. They usually grow near the surface of the water because light cannot penetrate very far through the water.

Algae are controlled in raw waters with chlorine and potassium permanganate. Algal blooms in raw water reservoirs are often controlled with copper sulfate.

Note: By producing oxygen, which is utilized by other organisms including animals, algae play an important role in the balance of nature.

2.6.1 IMPORTANCE OF INTERACTIONS BETWEEN BACTERIA AND ALGAE

The presence of both algae and bacteria is essential for the proper functioning of a treatment pond. Bacteria break down the complex organic waste components found in anaerobic and aerobic pond environments into simple compounds, which are then available for uptake by the algae. Algae, in turn, produce the O_2 necessary for the survival of aerobic bacteria. The pond reactions of biodegradation and mineralization of waste material by bacteria and the synthesis of new organic compounds in the form of algal cells can result in a pond effluent containing a higher than acceptable level of total suspended solids (TSS). Although this form of TSS does not contain the same constituents as the influent TSS, it does contribute to turbidity and must be removed before the effluent is discharged. Once concentrated and removed, depending on regulatory requirements, algal TSS may be used as a nutrient for use in agriculture or as a feed supplement.

2.7 INVERTEBRATES

Although bacteria and algae are the primary organisms through which waste stabilization is accomplished, predator life forms also play a role in wastewater pond ecology. It has been suggested that the planktonic invertebrate *Cladocera* spp. and the benthic invertebrate family Chironomidae are the most significant fauna in the pond community in terms of stabilizing organic material. The cladocerans feed on the algae and promote flocculation and settling of particulate matter. This in turn results in better light penetration and algal growth at greater depths. Settled matter is

further broken down and stabilized by the benthic-feeding Chironomidae. Predators, such as rotifers, often control the population levels of certain of the smaller life forms in the pond, thereby influencing the succession of species throughout the seasons.

Mosquitoes can present a problem in some ponds. Aside from their nuisance characteristics, certain mosquitoes are also vectors for such diseases as encephalitis, malaria, and yellow fever, and they constitute a hazard to public health that must be controlled. *Gambusia*, commonly called mosquito fish, have been introduced to eliminate mosquito problems in some ponds in warm climates (Pearson, 2005; Pipes, 1961; Ullrich, 1967), but their introduction has been problematic as they can outcompete native fish that also feed on mosquito larvae. There are also biochemical controls, such as the larvicides *Bacillus thuringiensis israelensis* (Bti), and Abate®, which may be effective if the product is applied directly to the area containing mosquito larvae. The most effective means of control of mosquitoes in ponds is the control of emergent vegetation (USEPA, 2011).

Protozoans (“first animals”) are a large group of eucaryotic organisms of more than 50,000 known species belonging to the kingdom Protista that have adapted a form of cell to serve as the entire body. In fact, protozoans are one-celled, animal-like organisms with complex cellular structures. In the microbial world, protozoans are giants, many times larger than bacteria. They range in size from 4 to 500 microns. The largest ones can almost be seen by the naked eye. They can exist as solitary or independent organisms—for example, stalked ciliates (Figure 2.3) such as *Vorticella*—or they can colonize (e.g., sedentary *Carchesium*). Protozoans get their name because they employ the same type of feeding strategy as animals; that is, they are heterotrophic, meaning they obtain cellular energy from organic substances such as proteins. Most are harmless, but some are parasitic. Some forms have two life stages: active trophozoites (capable of feeding) and dormant cysts.

The major groups of protozoans are based on their method of locomotion (motility). The Mastigophora, for example, utilize one or more *flagella*, the whip-like projection that propels the free-swimming organisms; *Giardia lamblia* is an example of a flagellated protozoan. Ciliophora move by means of shortened modified flagella called *cilia* (short hair-like structures that beat rapidly and propel them through the water). Sarcodina utilize amoeboid movement, a streaming or gliding action; the shape of amoebae change as they stretch and then contract to move from place to place. Sporozoa are nonmotile; they are simply swept along, riding the currents of the water.

Protozoans consume organics to survive; their favorite food is bacteria. Protozoans are usually aerobic or facultative with regard to oxygen requirements. Toxic materials, pH, and temperature affect protozoan rates of growth in the same way as they affect bacteria. Most protozoan life cycles alternate between an active growth phase (*trophozoites*) and a resting stage (*cysts*). Cysts are extremely resistant structures that protect the organism from destruction when it encounters harsh environmental conditions—including chlorination.

Note: Protozoans that are resistant to chlorination require higher disinfectant concentrations and longer contact time for disinfection than those normally used in water treatment.

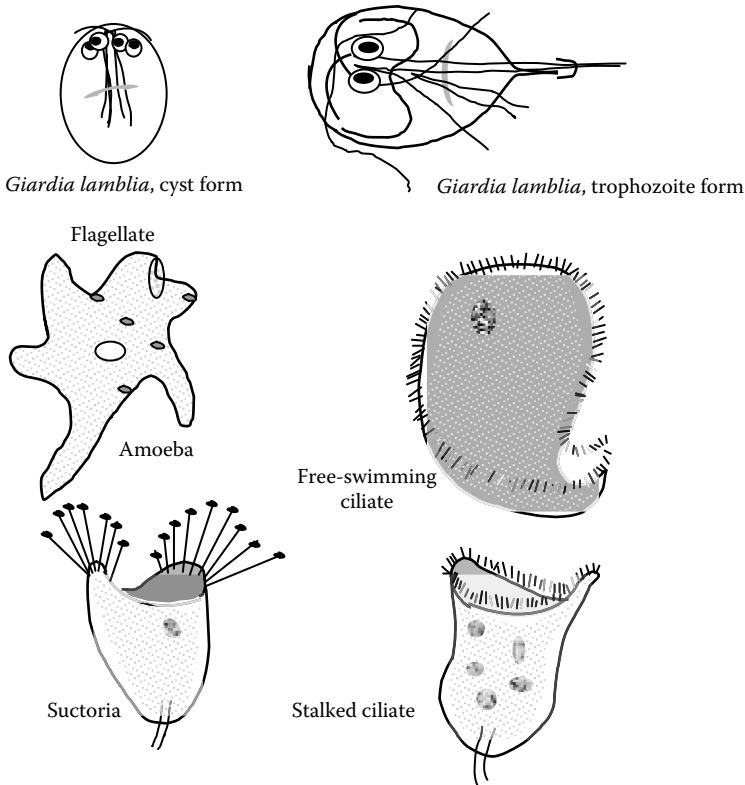


FIGURE 2.3 Protozoa.

In wastewater treatment, protozoans are a critical part of the purification process and can be used to indicate the condition of treatment processes. Protozoans normally associated with wastewater include amoebae, flagellates, free-swimming ciliates, and stalked ciliates. Amoebae are associated with poor wastewater treatment of a young biosolids mass (Figure 2.3). They navigate through wastewater in a streaming or gliding motion accomplished by the movement of liquids stored within their cell walls. They are normally associated with an effluent high in BOD and suspended solids.

Flagellates (flagellated protozoans) have a single, long hair-like or whip-like projection (flagella) that is used to propel the free-swimming organisms through wastewater and to attract food (see Figure 2.3). Flagellated protozoans are normally associated with poor treatment and young biosolids. When the predominant organism is the flagellated protozoa, the plant effluent will contain large amounts of BOD and suspended solids.

The free-swimming ciliated protozoan uses its tiny, hair-like projections (cilia) to move itself through the wastewater and to attract food (see Figure 2.3). The free-swimming ciliated protozoan is normally associated with a moderate biosolids age and effluent quality. When the free-swimming ciliated protozoan is the predominant organism, the plant effluent will normally be turbid and contain a high amount of

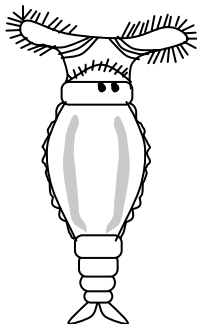


FIGURE 2.4 *Philodina*, a common rotifer.

suspended solids. The stalked ciliated protozoan attaches itself to the wastewater solids and uses its cilia to attract food (see Figure 2.3). The stalked ciliated protozoan is normally associated with a plant effluent that is very clear and contains low amounts of both BOD and suspended solids.

Rotifers are a well-defined group of the smallest, simplest multicellular microorganisms; they are found in nearly all aquatic habitats (Figure 2.4). Rotifers are a higher life form associated with cleaner waters. Normally found in well-operated wastewater treatment plants, they can be used to indicate the performance of certain types of treatment processes.

Because they are important members of freshwater zooplankton, microscopic *crustaceans* are of interest to wastewater operators. These microscopic organisms are characterized by a rigid shell structure. These multicellular animals are strict aerobes, and as primary producers they feed on bacteria and algae. They are important as a source of food for fish. Additionally, microscopic crustaceans have been used to clarify algae-laden effluents from oxidation ponds. *Cyclops* and *Daphnia* are two microscopic crustaceans of interest to water and wastewater operators.

2.8 POND MACROINVERTEBRATES

To this point, a few organisms important to successful operation of wastewater stabilization ponds have been discussed. In this section, pond macroinvertebrates of significance are described and discussed. The macroinvertebrates are the best-studied and most diverse animals in ponds and streams.

2.8.1 MACROINVERTEBRATE KEY TERMS

Abdomen—The third main division of the body; behind the head and thorax.

Anterior—In front (before).

Apical—Near or pertaining to the end of any structure; part of the structure that is farthest from the body.

Basal—Pertaining to the end of any structure that is nearest to the body.

Burrower—Animal that uses a variety of structures designed for moving and burrowing into sand and silt or for building tubes within loose substrate.

Carapace—The hardened part of some arthropods that spreads like a shield over several segments of the head and thorax.

Caudal filament—Threadlike projection at the end of the abdomen, like a tail.

Clinger—Animal that uses claws or hooks to cling to surfaces, such as rocks, plants, or other hard surfaces; it often moves slowly along these surfaces.

Concentric—A growth pattern on the opercula of some gastropods, marked by a series of circles that lie entirely within each other; compare multispiral and paucispiral.

Crawler—An animal whose main means of locomotion is moving slowly along the bottom; usually has some type of hooks, claws, or specially designed feet to help hold onto surfaces.

Detritus—Disintegrated or broken up mineral or organic material.

Dextral—The curvature of a gastropod shell where the opening is visible on the right when the spire is point up.

Distal—Near or toward the free end of any appendage; that part farthest from the body.

Dorsal—Pertaining to or situated on the back or top, especially of the thorax and abdomen.

Elytra—Hardened shell-like mesothoracic wings of adult beetles (Coleoptera).

Femur—The leg section between the tibia and coxa of Arthropoda, comparable to an upper arm or thigh.

Flagella—Small fingerlike or whip-like projections.

Gill—Any structure especially adapted for the exchange of dissolved gases between an animal and the surrounding liquid.

Glossae—Lobes front and center on the labium; in Plecoptera, the lobes are between the paraglossae.

Hemimetabolism—Incomplete metamorphosis.

Holometabolism—Complete metamorphosis.

Labium—Lower mouthpart of an arthropod, like a jaw or lip.

Labrum—Upper mouthpart of an arthropod consisting of a single, usually hinged plate above the mandibles.

Lateral—Feature or marking located on the side of a body or other structure.

Ligula—The ventral wall of an arthropod's oral cavity.

Lobe—A rounded projection or protuberance.

Mandibles—The first pair of jaws in insects.

Maxillae—The second pair of jaws in insects.

Multispiral—The growth pattern on the opercula of some gastropods marked by several turns from the center to the edge.

Operculum—A lid or covering structure, like a door to an opening.

Palpal lobes—The grasping pinchers at the end of the Odonata lower jaw.

Paucispiral—A growth pattern on the opercula of some gastropods marked by a few turns from the center to the edge.

Periphyton—Algae and associated organisms that live attached to underwater surfaces.

Posterior—Behind; opposite of anterior.

Proleg—Any projection appendage that supports locomotion or attachment.

Prothorax—The first thoracic segment closest to the head.

Rostrum—A beak or beak-like mouthpart.

Sclerite—A hardened area of an insect body wall, usually surrounded by softer membranes.

Seta (pl. *setae*)—Hair-like projection.

Sinistral—The curvature of a gastropod shell where the opening is seen on the left when the spire is pointed up.

2.8.2 INSECT MACROINVERTEBRATES

The most important insect groups in facultative ponds are Coleoptera (beetles, such as whirligig beetles and their larvae), Odonata (dragonflies and damselflies), Chironomidae (midge flies and their larvae), Corixidae (water boatman), and Gastropoda (snails). The identification of these different orders is usually easy, and many keys and specialized references (e.g., Merritt and Cummins, 1996) are available to help in the identification of species. Insect macroinvertebrates are ubiquitous in streams and are often represented by many species.

2.8.2.1 True Flies—Midge Fly, Midge Larvae (Order: Diptera)

Description: Head may be a capsule-like structure with thick hard skin; it may be partially reduced so that it appears to be part of the thorax, or it may be greatly reduced with only the mouthparts visible; no wing pads occur on the thorax; false legs (pseudo-legs) may extend from various sections of the thorax and abdomen composed of entirely soft skin, but some families have hardened plates scattered on various body features. The larval states do not have segmented leg features.

True or two- (*di-*) winged (*ptera*) flies include not only the flies that we are most familiar with, such as fruitflies and houseflies, but also midges (Figure 2.5), mosquitoes, crane flies, and others. Houseflies and fruitflies live only on land, and we do not concern ourselves with them. Some, however, spend nearly their entire lives in water and contribute to the ecology of streams.

True fly larvae may eat almost anything, depending on their species. Those with brushes on their heads use them to strain food out of the water that passes through. Others may eat algae, detritus, plants, and even other fly larvae.

Diptera serve an important role in cleaning water and breaking down decaying material, and they are a vital food source for many of the animals living in and around streams, as they play pivotal roles in the processing of food energy. The true flies most familiar to us, however, are the midge flies, mosquitoes, and crane flies, because they are pests. Some midge flies and mosquitoes bite; the crane fly does not bite but looks like a giant mosquito.

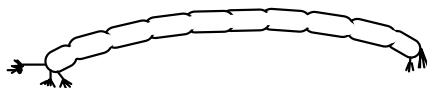


FIGURE 2.5 Midge larvae.

Like mayflies, stoneflies, and caddisflies, true flies are mostly in larval form. Just as for caddisflies, we can find their pupae, because they are holometabolous insects; that is, they go through complete metamorphosis. Most of them are free living and travel around. Although none of the true fly larvae has the six-jointed legs that we see on other insects in the stream, they sometimes have strange little prolegs to move around with. Others may move somewhat like worms do, and some—the ones that live in waterfalls and rapids—have a row of six suction discs that they use to move much like a caterpillar does. Many use silk pads and hooks at the ends of their abdomens to hold them fast to smooth rock surfaces.

2.8.2.2 Beetles (Order: Coleoptera)

Description: Head has thick hardened skin; thorax and abdomen of most adult families have moderately hardened skin, several larvae have a soft-skinned abdomen; there are no wing pads on the thorax in most larvae, but wing pads are usually visible on adults; three pairs of segmented legs attach to the thorax; no structures. Projections may extend from the sides of the abdomen in most adult families, but some larval stages have flat plates or filaments; no prolegs or long tapering filaments at the end of the abdomen. Beetles are one of the most diverse insect groups but are not as common in aquatic environments.

Of the more than 1 million described species of insect, at least one third are beetles, making Coleoptera not only the largest order of insects but also the most diverse order of living organisms. Even though this is the most speciose order of terrestrial insects, surprisingly their diversity is not so apparent in running waters. Coleoptera belong to the infraclass Neoptera, division Endopterygota. Members of this order have an anterior pair of wings (*elytra*) that are hard and leathery and not used in flight; the membranous hindwings, which are used for flight, are concealed under the elytra when the organisms are at rest. Only 10% of the 350,000 described species of beetles are aquatic.

Beetles are holometabolous. Eggs of aquatic coleopterans hatch in 1 or 2 weeks, with diapause occurring rarely. Larvae undergo from three to eight molts. The pupal phase of all coleopterans is technically terrestrial, making this life stage of beetles the only one that has not successfully invaded the aquatic habitat. A few species have diapausing prepupae, but most complete transformation to adults in 2 to 3 weeks. Terrestrial adults of aquatic beetles are typically short lived and sometimes nonfeeding, like those of the other orders of aquatic insects. The larvae of Coleoptera are morphologically and behaviorally different from the adults, and their diversity is high.

Aquatic species occur in two major suborders, the Adephaga and the Polyphaga. Both larvae and adults of six beetle families are aquatic: Dytiscidae (predaceous diving beetles), Elmidae (riffle beetles), Gyrinidae (whirligig beetles), Halipidae (crawling water beetles), Hydrophilidae (water scavenger beetles), and Noteridae (burrowing water beetles). Five families—Chrysomelidae (leaf beetles), Limnichidae (marsh-loving beetles), Psephenidae (water pennies), Ptilodactylidae (toe-winged beetles), and Scirtidae (marsh beetles)—have aquatic larvae and terrestrial adults, as do most of the other orders of aquatic insects; adult limnichids, however, readily submerge when disturbed. Three families have species

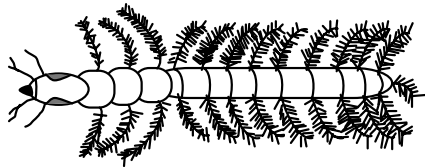


FIGURE 2.6 Whirligig beetle larva.

that are terrestrial as larvae and aquatic as adults, a highly unusual combination among insects: Curculionidae (weevils), Dryopidae (long-toed water beetles), and Hydraenidae (moss beetles). Because they provide a greater understanding of the condition of a freshwater body (i.e., they are useful indicators of water quality), we focus our discussion here on the whirligig beetle.

Whirligig beetles are common inhabitants of streams and normally are found on the surface of quiet pools. The body of a whirligig beetle has pincher-like mouthparts and six segmented legs on the middle of the body; the legs end in tiny claws. Many filaments extend from the sides of the abdomen. They have four hooks at the end of the body and no tail (Figure 2.6).

Note: When disturbed, whirligig beetles swim erratically or dive while emitting defensive secretions.

As larvae, they are benthic predators, whereas the adults live on the water surface, attacking dead and living organisms trapped in the surface film. They occur on the surface in aggregations of up to thousands of individuals. Unlike the mating swarms of mayflies, these aggregations serve primarily to confuse predators. Whirligig beetles have other interesting defensive adaptations—for example, the Johnston's organ at the base of the antennae enables them to echolocate using surface-wave signals; their compound eyes are divided into two pairs, one above and one below the water surface, enabling them to detect both aerial and aquatic predators; and they produce noxious chemicals that are highly effective at deterring predatory fish.

2.8.2.3 Dragonflies and Damselflies (Order: Odonata)

Description: The lower lip (labium) of the dragonfly is long and elbowed to fold back against the head when not feeding, thus concealing other mouthparts; wing pads are present on the thorax; three pairs of segmented legs attach to the thorax; there are no gills on the sides of the abdomen; three pointed structures may occur at the end of the abdomen forming a pyramid-shaped opening; bodies are long and stout or somewhat oval. Damselflies have three flat gills at the end of the abdomen forming a tail-like structure, and their bodies are long and slender.

The order Odonata, which includes dragonflies (Suborder: Anisoptera) and damselflies (Suborder: Zygoptera), is a small order of conspicuous, hemimetabolous insects (lacking a pupal stage) representing about 5000 named species and 23 families worldwide. *Odonata* is a Greek word meaning “toothed one,” referring to the serrated teeth located on the insect’s chewing mouthparts (mandibles). Characteristics of dragonfly and damselfly larvae include the following:

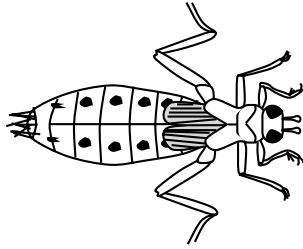


FIGURE 2.7 Dragonfly nymph.

- Large eyes
- Three pairs of long segmented legs on the upper middle section (thorax) of body
- Large scoop-like lower lip that covers the bottom of the mouth
- No gills on the sides or underneath the abdomen

Note: Dragonflies and damselflies are unable to fold their four elongated wings back over the abdomen when at rest.

Dragonflies and damselflies are medium to large insects with two pairs of long equal-sized wings. The body is long and slender, with short antennae. Immature stages are aquatic, and development occurs in three stages (egg, nymph, adult).

Dragonflies are also known as *darning needles* (at one time, children were warned to keep quiet or the dragonfly's darning needles would sew the child's mouth shut). In their nymphal stage, dragonflies are grotesque creatures, robust and stoutly elongated. They do not have long tails (Figure 2.7). They are commonly gray, greenish, or brown to black in color. They are medium to large aquatic insects, ranging in size from 15 to 45 mm; the legs are short and used for perching. They are often found on submerged vegetation and at the bottom of streams in the shallows. They are rarely found in polluted waters. Their food consists of other aquatic insects, annelids, small crustacea, and mollusks. Transformation occurs when the nymph crawls out of the water, usually onto vegetation. There it splits its skin and emerges prepared for flight. The adult dragonfly is a strong flier, capable of great speed (>60 mph) and maneuverability. (They can fly backward, stop on a dime, zip 20 feet straight up, and slip sideways in the blink of an eye!) When the dragonfly is at rest, its wings remain open and out to the sides of the body. A dragonfly's freely movable head has large, hemispherical eyes (nearly 30,000 facets each), which give the insects the excellent vision necessary to locate prey. Dragonflies eat small insects, mainly mosquitoes (large numbers of mosquitoes), while in flight. Depending on the species, dragonflies lay hundreds of eggs by dropping them into the water and leaving them to hatch or by inserting eggs singly into a slit in the stem of a submerged plant. The incomplete metamorphosis (egg, nymph, mature nymph, and adult) can take 2 to 3 years. Nymphs are often covered by algal growth.

Note: Adult dragonflies are sometimes referred to as *mosquito hawks* because they eat such a large number of mosquitoes, which they catch while they are flying.

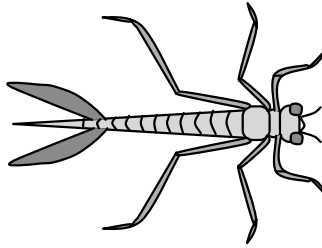


FIGURE 2.8 Damselfly nymph.

Damselflies are smaller and more slender than dragonflies. They have three long, oar-shaped feathery tails, which are actually gills, and long slender legs (Figure 2.8). They are gray, greenish, or brown to black in color. Their habits are similar to those of dragonfly nymphs, and they emerge from the water as adults in the same manner. The adult damselflies are slow and seem uncertain in flight. Wings are commonly black or clear, and the body is often brilliantly colored. When at rest, they perch on vegetation with their wings closed upright. Damselflies mature in 1 to 4 years. Adults live for a few weeks or months. Unlike the dragonflies, adult damselflies rest with their wings held vertically over their backs. They mostly feed on live insect larvae.

Note: Relatives of the dragonflies and damselflies are some of the most ancient of the flying insects. Fossils have been found of giant dragonflies with wingspans up to 720 mm (28.4 inches) that lived long before the dinosaurs!

2.8.3 NON-INSECT MACROINVERTEBRATES

Non-insect macroinvertebrates are important to our discussion of stream and fresh-water ecology because many of them are used as bioindicators of stream quality. Three frequently encountered groups in running water systems are Oligochaeta (worms), Hirudinea (leeches), and Gastropoda (lung-breathing snails). They are by no means restricted to running-water conditions, and the great majority of them occupy slow-flowing marginal habitats where the sedimentation of fine organic materials takes place.

2.8.3.1 Gastropoda (Lung-Breathing Snail)

Lung-breathing snails (pulmonates) may be found in streams that are clean; however, their dominance may indicate that dissolved oxygen levels are low. These snails are different from *right-handed snails* because they do not breathe under water by use of gills but instead have a lung-like sac called a *pulmonary cavity*, which they fill with air at the surface of the water. When the snail takes in air from the surface, it makes a clicking sound. The air taken in can enable the snail to breathe under water for long periods, sometimes hours.

Lung-breathing snails have two characteristics that help us to identify them. First, they have no operculum or hard cover over the opening to the body cavity. Second, snails are either right-handed or left-handed; the lung-breathing snails are

left-handed. We can tell the difference by holding the shell so that its tip is upward and the opening toward us. If the opening is to the left of the axis of the shell, the snail is considered to be *sinistral*—that is, it is left-handed. If the opening is to the right of the axis of the shell, the snail is *dextral*—that is, it is right-handed and it breathes with gills. Snails are animals of the substrate and are often found creeping along on all types of submerged surfaces in water from 10 cm to 2 m deep.

2.8.4 IN THE POND, IT IS WHAT EATS WHAT THAT IS IMPORTANT

In the sections above, most of the typical organisms that may be present in a healthy and properly operated facultative wastewater stabilization pond were described and discussed. The importance of these organisms and others is significant. The overall importance of these organisms is probably best demonstrated by describing who eats whom. This is important because in their normal feeding habit of devouring waste to purify the wastestream before it is discharged for further treatment or outfallen to the receiving water body, they eventually feed on other microorganisms. For example, *Daphnia*, Gastropoda, and protozoans eat bacteria. Corixidae, Chironomidae, *Daphnia*, Gastropoda, and protozoans eat algae. *Daphnia*, Corixidae, and Odonata eat protozoans. Snails are eaten by *Helobdella stagnalis* (leeches). Higher pond plants are eaten by Chironomidae and Gyrinidae. This eating circle continues as long as the facultative treatment pond is provided waste that is not toxic to the organisms.

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3 Biochemistry in a Wastewater Stabilization Pond

3.1 PHOTOSYNTHESIS

Photosynthesis is the process whereby organisms use solar energy to fix carbon dioxide (CO₂) and obtain the reducing power to convert it to organic compounds. In wastewater ponds, the dominant photosynthetic organisms include algae, cyanobacteria, and purple sulfur bacteria (Pearson, 2005; Pipes, 1961). Photosynthesis may be classified as oxygenic or anoxygenic, depending on the source of reducing power used by a particular organism. In oxygenic photosynthesis, water serves as the source of reducing power, and O₂ is a byproduct. The equation representing oxygenic photosynthesis is



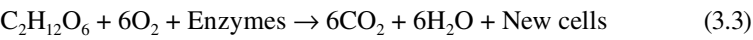
Oxygenic photosynthetic algae and cyanobacteria convert CO₂ to organic compounds, which serve as the major source of chemical energy for other aerobic organisms. Aerobic bacteria require the O₂ produced to function in their role as primary consumers in degrading complex organic waste material.

Anoxygenic photosynthesis does not produce O₂ and, in fact, occurs in the complete absence of O₂. The bacteria involved in anoxygenic photosynthesis are largely strict anaerobes, unable to function in the presence of O₂. They obtain energy by reducing inorganic compounds. Many photosynthetic bacteria utilize reduced sulfur compounds or elemental sulfur (S⁰) in anoxygenic photosynthesis according to the following equation:



3.2 RESPIRATION

Respiration is a physiological process by which organic compounds are oxidized into CO₂ and water. Respiration is also an indicator of cell material synthesis. It is a complex process that consists of many interrelated biochemical reactions (Pearson, 2005; Stanier et al., 1963). Aerobic respiration, common to species of bacteria, algae, protozoans, invertebrates, and higher plants and animals, may be represented by the following equation:



The bacteria involved in aerobic respiration are primarily responsible for the degradation of waste products.

In the presence of light, respiration and photosynthesis can occur simultaneously in algae; however, the respiration rate is low compared to the photosynthesis rate, which results in a net consumption of CO₂ and production of O₂. In the absence of light, on the other hand, algal respiration continues while photosynthesis stops, resulting in a net consumption of O₂ and production of CO₂ (USEPA, 2011).

3.3 NITROGEN CYCLE

The nitrogen (N) cycle occurring in a wastewater treatment pond consists of a number of biochemical reactions mediated by bacteria. Figure 3.1 provides a schematic representation of the changes in N speciation in wastewater ponds over a year. A more detailed discussion of the cycling of N species is presented later in this text.

Organic nitrogen and ammonia (NH₃) enter with the influent wastewater. Organic nitrogen in fecal matter and other organic materials undergo conversion to NH₃ and the ammonium ion NH₄⁺ by microbial activity. NH₃ may volatilize into the atmosphere. The rate of gaseous NH₃ losses to the atmosphere is primarily a function of pH, surface-to-volume ratio, temperature, and the mixing conditions. An alkaline pH shifts the equilibrium of NH₃ gas and NH₄⁺ toward gaseous NH₃ production, while the mixing conditions affect the magnitude of the mass transfer coefficient.

Ammonium is nitrified to nitrite (NO₂⁻) by the bacteria *Nitrosomonas* and then to nitrate (NO₃⁻) by *Nitrobacter*. The overall nitrification reaction is

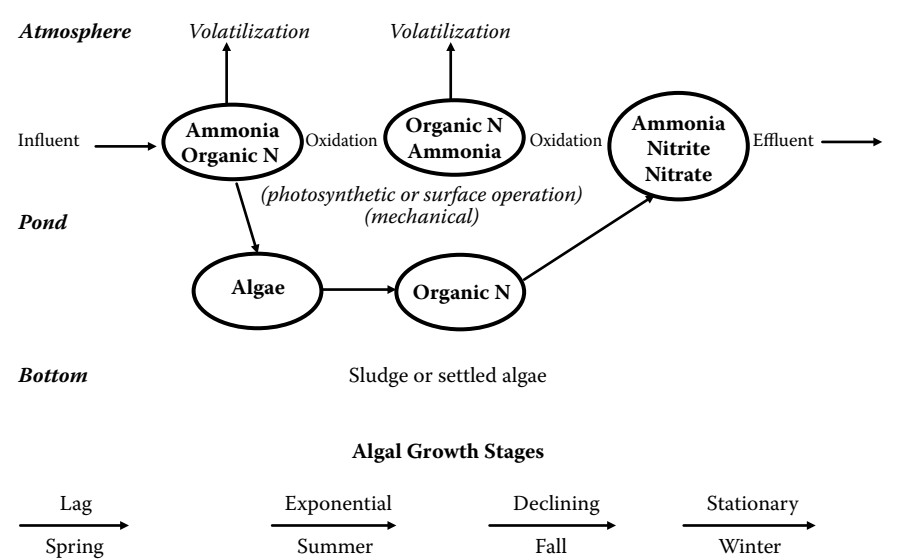
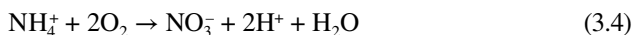
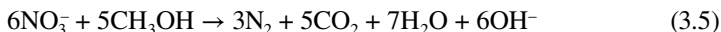


FIGURE 3.1 The nitrogen cycle in wastewater pond system.



The NO_3^- produced in the nitrification process, as well as a portion of the NH_4^+ produced from ammonification, can be assimilated by organisms to produce cell protein and other nitrogen-containing compounds. The NO_3^- may also be denitrified to form NO_2^- and then nitrogen gas. Several species of bacteria may be involved in the denitrification process, including *Pseudomonas*, *Micrococcus*, *Achromobacter*, and *Bacillus*. The overall denitrification reaction is



Nitrogen gas may be fixed by certain species of cyanobacteria when nitrogen is limited. This may occur in nitrogen-poor industrial ponds but rarely in municipal or agricultural ponds.

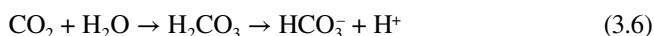
Nitrogen removal in facultative wastewater ponds can occur through any of the following processes: (1) gaseous NH_3 stripping to the atmosphere, (2) NH_4^+ assimilation in algal biomass, (3) NO_3^- uptake by floating vascular plants and algae, and (4) biological nitrification–denitrification. Whether NH_4^+ is assimilated into an algal biomass depends on the biological activity in the system and is affected by several factors such as temperature, organic load, detention time, and wastewater characteristics.

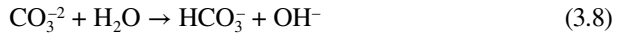
3.4 DISSOLVED OXYGEN

Oxygen is a partially soluble gas. Its solubility varies in direct proportion to the atmospheric pressure at any given temperature. Dissolved oxygen (DO) concentrations of approximately 8 mg/L are generally considered to be the maximum attainable under local ambient conditions. In mechanically aerated ponds, the limited solubility of O_2 determines its absorption rate (Sawyer et al., 1994). The natural sources of DO in ponds are photosynthetic oxygenation and surface reaeration. In areas of low wind activity, surface reaeration may be relatively unimportant, depending on the water depth. Where surface turbulence is created by excessive wind activity, surface reaeration can be significant. Experiments have shown that DO in wastewater ponds varies almost directly with the level of photosynthetic activity, which is low at night and early morning and rises during daylight hours to a peak in the early afternoon. At increased depth, the effects of photosynthetic oxygenation and surface reaeration decrease, as the distance from the water–atmosphere interface increases and light penetration decreases. This can result in the establishment of a vertical gradient. The microorganisms in the pond will segregate along the gradient.

3.5 PH AND ALKALINITY

In wastewater ponds, the hydrogen ion concentration, expressed as pH, is controlled through the carbonate buffering system represented by the following equations:





The equilibrium of this system is affected by the rate of algal photosynthesis. In photosynthetic metabolism, CO_2 is removed from the dissolved phase, forcing the equilibrium of the first expression (Equation 3.6) to the left. This tends to decrease the hydrogen ion (H^+) concentration and the bicarbonate (HCO_3^-) alkalinity. The effect of the decrease in HCO_3^- concentration is to force the third equation (Equation 3.8) to the left and the fourth (Equation 3.9) to the right, both of which decrease total alkalinity. The decreased alkalinity associated with photosynthesis will simultaneously reduce the carbonate hardness present in the water. Because of the close correlation between pH and photosynthetic activity, there is a diurnal fluctuation in pH when respiration is the dominant metabolic activity.

3.6 PHYSICAL FACTORS

3.6.1 LIGHT

The intensity and spectral composition of light penetrating a pond surface significantly affect all resident microbial activity. In general, activity increases with increasing light intensity until the photosynthetic system becomes light saturated. The rate at which photosynthesis increases in proportion to an increase in light intensity, as well as the level at which an organism's photosynthetic system becomes light saturated, depends upon the particular biochemistry of the species (Lynch and Poole, 1979; Pearson, 2005). In ponds, photosynthetic O_2 production has been shown to be relatively constant in the range of 5380 to 53,800 lumens/m² light intensity, with a reduction occurring at higher and lower intensities (Paterson and Curtis, 2005; Pipes, 1961).

The spectral composition of available light is also crucial in determining photosynthetic activity. The ability of photosynthetic organisms to utilize available light energy depends primarily upon their ability to absorb the available wavelengths. This absorption ability is determined by the specific photosynthetic pigment of the organism. The main photosynthetic pigments are chlorophylls and phycobilins. Bacterial chlorophyll differs from algal chlorophyll in both chemical structure and absorption capacity. These differences allow the photosynthetic bacteria to live below dense algal layers where they can utilize light not absorbed by the algae (Lynch and Poole, 1979; Pearson, 2005).

The quality and quantity of light penetrating the pond surface to any depth depend on the presence of dissolved and particulate matter as well as the water absorption characteristics. The organisms themselves contribute to water turbidity, further limiting the depth of light penetration. Given the light penetration interferences, photosynthesis is significant only in the upper pond layers. This region of net photosynthetic activity is called the *euphotic zone* (Lynch and Poole, 1979; Pearson, 2005).

Light intensity from solar radiation varies with the time of day and difference in latitudes. In cold climates, light penetration can be reduced during the winter by ice and snow cover. Supplementing the treatment ponds with mechanical aeration may be necessary in these regions during that time of year.

3.6.2 TEMPERATURE

Temperature at or near the surface of the aerobic environment of a pond determines the succession of predominant species of algae, bacteria, and other aquatic organisms. Algae can survive at temperatures of 5 to 40°C. Green algae show most efficient growth and activity at temperatures of 30 to 35°C. Aerobic bacteria are viable within a temperature range of 10 to 40°C, and temperatures ranging from 35 to 40°C are optimum for cyanobacteria (Anderson and Zweig, 1962; Crites et al., 2006; Gloyna, 1976; Paterson and Curtis, 2005).

Because a major source of heat for these systems is solar radiation, a temperature gradient can develop in a pond with depth. This will influence the rate of anaerobic decomposition of solids that have settled at the bottom of the pond. The bacteria responsible for anaerobic degradation are active in temperatures from 15 to 65°C. When they are exposed to lower temperatures, their activity is reduced. The other major source of heat is the influent water. In sewerage systems with no major inflow or infiltration problems, the influent temperature is higher than that of the pond contents. Cooling influences are exerted by evaporation, contact with cooler groundwater, and wind action.

The overall effect of temperature in combination with light intensity is reflected in the fact that nearly all investigators report improved performance during summer and autumn months when both temperature and light are at their maximum. The maximum practical temperature of wastewater ponds is likely less than 30°C, indicating that most ponds operate at less than optimum temperature for anaerobic activity (Crites et al., 2006; Oswald, 1968, 1996; Paterson and Curtis, 2005).

During certain times of the year, cooler, more dense water remains at depth while the warmer water stays at the surface. Water temperature differences may cause ponds to stratify throughout their depth. As the temperature decreases during the fall and the surface water cools, stratification decreases and the deeper water mixes with the cooling surface water. This phenomenon is called *mixis*, or pond or lake overturn. As the density of water decreases and the temperature falls below 4°C, winter stratification can develop. When the ice cover breaks up and the water warms, a spring overturn can also occur. Pond overturn, which releases odorous compounds into the atmosphere, can generate complaints from property owners living downwind of the pond. The potential for pond overturn during certain times of the year is the reason why regulations may specify that ponds be located downwind, based on prevailing winds during overturn periods, and away from dwellings.

3.6.3 WIND

Prevailing and storm-generated wind should be factored into pond design and siting, as it influences performance and maintenance in several significant ways:

- *Oxygen transfer and dispersal*—By producing circulatory flows, winds provide the mixing necessary for O₂ transfer and diffusion below the surface of facultative ponds. This mixing action also helps disperse microorganisms and augments the movement of algae, particularly green algae.
- *Prevention of short-circuiting and reduction of odor events*—Care must be taken during design to position the pond inlet/outlet axis perpendicular to the direction of prevailing winds to reduce short-circuiting, which is the most common cause of poor performance. Consideration must also be made for the transport and fate of odors generated by treatment byproducts in anaerobic and facultative ponds.
- *Disturbance of pond integrity*—Waves generated by strong prevailing or storm winds are capable of eroding or overtopping embankments. Some protective material should extend one or more feet above and below the water level to stabilize earthen berms.
- *Hydraulic retention time*—A study by Wong and Lloyd (2004) indicated that wind effects can reduce hydraulic retention time.

DID YOU KNOW?

When we speak of hydraulic retention time (HRT), we might be referring to either the theoretical hydraulic retention time or the mean hydraulic retention time of a pond. What is the difference? The theoretical HRT is simply calculated by

$$\theta_{Theo} = V \div Q$$

where

θ_{Theo} = Theoretical hydraulic retention time (days).

V = Pond volume (m³).

Q = Average (or design) flow rate (m³/day).

In reality, ponds do not operate at their theoretical HRT, because

- Compared to the constant value used to calculate the theoretical HRT, in reality the flow rate is constantly changing.
- They are partly filled with sludge.

Even if a pond was operating at its theoretical HRT, its hydraulic efficiency is still likely to be suboptimal due to

- Hydraulic dead space
- Hydraulic short-circuiting

To investigate the hydraulic efficiency of a pond and to determine its mean HRT, a tracer test must be undertaken (Shilton and Harrison, 2003).

DID YOU KNOW?

The variation in pH in a facultative pond normally occurs in the upper aerobic zone, whereas the anaerobic and facultative zones will be relatively constant. This variation happens due to the changes that occur in the concentration of dissolved carbon dioxide. When carbon dioxide is dissolved in water it forms a weak carbonic acid, which would tend to lower pH. The relationship between algae and bacteria affects the carbon dioxide levels. During intense photosynthesis, algae use carbon dioxide and produce oxygen to be used by bacteria to assimilate organic wastes. The algae use much of the carbon dioxide, and the pH can rise significantly (pH values in the range of 11 to 12 are not uncommon). During the night or during cloudy weather, the algae respire and active photosynthesis does not occur. The bacteria continue to use up oxygen and produce carbon dioxide. This can cause a significant drop in the pond pH, especially if the influent wastewater has low alkalinity. This same pH swing can occur in natural ponds, lakes, and stream impoundments. During peak summer algae activity, the dissolved oxygen of stream impoundments varies from dawn levels of less than 1 mg/L to later afternoon values of 13 to 15 mg/L (supersaturation).

3.7 POND NUTRITIONAL REQUIREMENTS

To function as designed, the wastewater pond must provide sufficient macro- and micronutrients for the microorganisms to grow and populate the system adequately. It should be understood that a treatment pond system should be neither overloaded nor underloaded with wastewater nutrients.

DID YOU KNOW?

What is *dead space*? When looking downward at a wastewater stabilization pond from the surface, because of the contents of the wastestream entering the pond we usually see only the water that is on the surface. We do not see the solids that settle in bottom areas of the pond. This volume of settled sludge is dead space. As such, it reduces the effective volume of the pond, thereby reducing hydraulic and treatment efficiency. The same term is also used to refer to areas (e.g., corners) that are out of the main flow path. The concept of dead space should not be confused with the term *stagnant*, which is misleading because most of the fluid in a pond is moving to some extent. The water does not just sit or settle in the pond but moves and eventually is outfallen to a receiving body or to another downstream unit treatment process (Shilton and Harrison, 2003). The key point to remember about pond dead space is that it reduces the pond's effective treatment volume and therefore its overall treatment efficiency.

3.7.1 NITROGEN

Nitrogen (N) can be a limiting nutrient for primary productivity in a pond. The conversion of organic nitrogen to various other nitrogen forms results in a total net loss (Assenzo and Reid, 1966; Craggs, 2005; Middlebrooks and Pano, 1983; Middlebrooks et al. 1982; Pano and Middlebrooks, 1982). This nitrogen loss may be due to algal uptake or bacterial action. It is likely that both mechanisms contribute to the overall total nitrogen reduction. Another factor contributing to the reduction of total nitrogen is the removal of gaseous NH_3 under favorable environmental conditions. Regardless of the specific removal mechanism involved, NH_3 removal in facultative wastewater ponds has been observed at levels greater than 90%, with the major removal occurring in the primary cell of a multicell pond system (Crites et al., 2006; Middlebrooks et al., 1982; Shilton, 2005).

3.7.2 PHOSPHORUS

Phosphorus (P) is most often the growth-limiting nutrient in aquatic environments. Municipal wastewater in the United States is normally enriched in phosphorus, even though some states' restrictions on phosphorus-containing compounds in laundry detergents have resulted in reduced concentrations since the 1970s. All 50 states now have bans on phosphates (PO_4^{3-}) in laundry detergent; however, phosphate content limits for automatic dishwashing detergents and other household cleaning agents containing phosphorus remain unchanged in most states. With a contribution of approximately 15%, the concentration of phosphorus from wastewater treatment plants is still adequate to promote growth in aquatic organisms (Canada Department of Justice, 2014).

In aquatic environments, phosphorus occurs in three forms: (1) particulate phosphorus, (2) soluble organic phosphorus, and (3) inorganic phosphorus. Inorganic phosphorus, primarily in the form of orthophosphate (OP(OR)_3), is readily utilized by aquatic organisms. Some organism may store excess phosphorus as polyphosphate. At the same time, some PO_4^{3-} is continuously lost to sediments, where it is locked up in insoluble precipitates (Craggs, 2005; Crites et al., 2006; Lynch and Poole, 1979).

Phosphorus removal in ponds occurs via physical mechanisms such as adsorption, coagulation, and precipitation. The uptake of phosphorus by organisms in metabolic functions as well as for storage can also contribute to its removal. Removal in wastewater ponds has been reported to range from 30 to 95% (Assenzo and Reid, 1966; Crites et al., 2006; Pearson, 2005). Algae discharged in the final effluent may introduce organic phosphorus to receiving waters. Excessive algal "afterblossoms" observed in waters receiving effluents have, in some cases, been attributed to nitrogen and phosphorus compounds remaining in the treated wastewater.

3.7.3 SULFUR

Sulfur (S) is a required nutrient for microorganisms, and it is usually present in sufficient concentration in natural waters. Because sulfur is rarely limiting, its removal from wastewater is usually not considered necessary. Ecologically, sulfur compounds

such as hydrogen sulfide (H_2S) and sulfuric acid (H_2SO_4) are toxic, while the oxidation of certain sulfur compounds is an important energy source for some aquatic bacteria (Lynch and Poole, 1979; Pearson, 2005).

3.7.4 CARBON

The decomposable organic carbon (C) content of a waste is traditionally measured in terms of its biochemical oxygen demand (BOD_5), or the amount of oxygen required under standardized conditions for the aerobic biological stabilization of the organic matter over a certain period of time. Because complete treatment by biological oxidation can take several weeks, depending on the organic material and the organism present, standard practice is to use the BOD_5 as an index of the organic carbon content or organic strength of a waste. The removal of BOD_5 is a primary criterion by which treatment efficiency is evaluated. BOD_5 reduction in wastewater ponds ranging from 50 to 95% has been reported in the literature. Various factors affect the rate of reduction of BOD_5 . A very rapid reduction occurs in a wastewater pond during the first 5 to 7 days. Subsequent reductions take place at a sharply reduced rate. BOD_5 removals are generally much lower during winter and early spring than in summer and early fall. Many regulatory agencies recommend that pond operations do not include discharge during cold periods.

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4 Pond Math Parameters*

4.1 INTRODUCTION

It is general knowledge that mathematics is the study of numbers and counting and measuring, but its associated collaterals are less well recognized. Simply, mathematics is more than numbers; it also involves the study of number patterns and relationships, and it is a way to communicate ideas. Perhaps, however, mathematics, more than anything, is a way of reasoning that is unique to human beings. No matter how we describe or define mathematics, one thing is certain: Without an understanding of mathematical units and conversion factors one might as well delve into the mysteries of deciphering hieroglyphics while blindfolded and lacking the sense of touch and reason.

4.2 METRIC SYSTEM AND SI UNITS

The United States is now the only industrialized country in the world that does not use the metric system (or SI) as its predominant system of measurement. This explains why the units most commonly used by wastewater pond designers, managers, and operators are based on the complicated English system of weights and measures. However, bench work is usually based on the metric system or the International System of Units (SI) due to the convenient relationship between milliliters (mL), cubic centimeters (cm³), and grams (g).

The SI is a modernized version of the metric system established by international agreement. The metric system of measurement was developed during the French Revolution and was first promoted in the United States in 1866. In 1902, proposed congressional legislation requiring the U.S. government to use the metric system exclusively was defeated by a single vote. Although we use both systems in this text, SI provides a logical and interconnected framework for all measurements in engineering, science, industry, and commerce. The metric system is much simpler to use than the existing English system, as all of its units of measurement are divisible by 10.

Before listing the various conversion factors commonly used in pond design and operation it is important to describe the prefixes commonly used in the SI system. These prefixes are based on the power of 10; for example, a kilogram is 1000 grams, and a centimeter is 1/100 of 1 meter. The 20 SI prefixes used to form decimal multiples and submultiples of SI units are given in Table 4.1. Note that the kilogram is the only SI unit with a prefix as part of its name and symbol. Because multiple prefixes

* Based on material found in Spellman, F.R. and Whiting, N., *Mathematics for Environmental Practitioners*, CRC Press, Boca Raton, FL, 2013.

TABLE 4.1
SI Prefixes

Factor	Name	Symbol	Factor	Name	Symbol
10 ²⁴	Yotta	Y	10 ⁻¹	Deci	d
10 ²¹	Zetta	Z	10 ⁻²	Centi	c
10 ¹⁸	Exa	E	10 ⁻³	Milli	m
10 ¹⁵	Peta	P	10 ⁻⁶	Micro	μ
10 ¹²	Tera	T	10 ⁻⁹	Nano	n
10 ⁹	Giga	G	10 ⁻¹²	Pico	p
10 ⁶	Mega	M	10 ⁻¹⁵	Femto	f
10 ³	Kilo	k	10 ⁻¹⁸	Atto	a
10 ²	Hecto	h	10 ⁻²¹	Zepto	z
10 ¹	Deka	da	10 ⁻²⁴	Yocto	y

may not be used, in the case of the kilogram the prefix names of Table 4.1 are used with the unit name “gram” and the prefix symbols are used with the unit symbol “g.” With this exception, any SI prefix may be used with any SI unit, including degree Celsius and its symbol, °C.

■ EXAMPLE 4.1

10⁻⁶ kg = 1 mg (one milligram), but not 10⁻⁶ kg = 1 μkg (1 microkilogram)

■ EXAMPLE 4.2

Consider the height of the Washington Monument. We may write it as 169,000 mm = 16,900 cm = 169 m = 0.169 km using the millimeter (SI prefix “milli,” symbol “m”), centimeter (SI prefix “centi,” symbol “c”), or kilometer (SI prefix “kilo,” symbol “k”).

4.3 CONVERSION FACTORS

Conversion factors are given in alphabetical order in Table 4.2 and in unit category listing order in Table 4.3.

■ EXAMPLE 4.3

Problem: Find degrees in Celsius of water at 72°F.

Solution:

$$^{\circ}\text{C} = (\text{F} - 32) \times 5/9 = (72 - 32) \times 5/9 = 22.2$$

4.3.1 CONVERSION FACTORS: PRACTICAL EXAMPLES

Sometimes we have to convert between different units. Suppose that a 60-inch piece of pipe is attached to an existing 6-foot piece of pipe. Joined together, how long are they? Obviously, we cannot find the answer to this question by adding 60 to 6, because

TABLE 4.2
Alphabetical List of Conversion Factors

Factor	Metric (SI) or English Conversions
°C	(5/9)[(°F) – 32°]
°F	(9/5)[(°C) + 32°]
1°C (expressed as an interval)	33.8°F = (9/5)(°F) 1.8°R (degrees Rankine) 1.0 K (degrees Kelvin)
1°F (expressed as an interval)	0.556°C = (5/9)°C 1.0°R (degrees Rankine) 0.556 K (degrees Kelvin)
1 atm (atmosphere)	1.013 bars 10.133 N/cm ² (newtons/square centimeter) 33.90 ft of H ₂ O (feet of water) 101.325 kPa (kilopascals) 1,013.25 mbar (millibars) psia (pounds/square inch absolute) 760 torr 760 mmHg (millimeters of mercury)
1 bar	0.987 atm (atmosphere) 1 × 10 ⁶ dynes/cm ² (dynes/square centimeter) 33.45 ft of H ₂ O (feet of water) 1 × 10 ⁵ Pa (pascals) 750.06 torr 750.06 mmHg (millimeters of mercury)
1 Bq (becquerel)	1 radioactive disintegration/second 2.7 × 10 ⁻¹¹ Ci (curie) 2.7 × 10 ⁻⁸ mCi (millicurie)
1 Btu (British thermal unit)	252 cal (calories) 1055.06 J (joules) 10.41 L-atm (liter-atmospheres) 0.293 Wh (watt-hour)
1 cal (calorie)	3.97 × 10 ⁻³ Btu (British thermal unit) 4.18 J (joules) 0.0413 L-atm (liter-atmospheres) 1.163 × 10 ⁻³ Wh (watt-hour)
1 Ci (curie)	3.7 × 10 ¹⁰ radioactive disintegrations/second 3.7 × 10 ¹⁰ Bq (becquerels) 1000 mCi (millicuries)
1 cm (centimeter)	0.0328 ft (foot) 0.394 in. (inch) 10,000 μm (microns, micrometers) 100,000,000 Å = 10 ⁸ Å (Ångstroms)
1 cm ² (square centimeter)	1.076 × 10 ⁻³ ft ² (square feet) 0.155 in. ² (square inch) 1 × 10 ⁻⁴ m ² (square meter)

TABLE 4.2 (continued)
Alphabetical List of Conversion Factors

Factor	Metric (SI) or English Conversions
1 cm ³ (cc, cubic centimeter)	3.53 × 10 ⁻⁵ ft ³ (cubic feet) 0.061 in. ³ (cubic inch) 2.64 × 10 ⁻⁴ gal (gallon) 52.18 L (liters) 52.18 mL (milliliters)
1 day	24 hr (hours) 1440 min (minutes) 86,400 sec (seconds) 0.143 wk (week) 2.738 × 10 ⁻³ yr (year)
1 dyne	1 × 10 ⁻⁵ N (newton)
1 erg	1 dyn-cm (dyne-centimeter) 1 × 10 ⁻⁷ J (joule) 2.78 × 10 ⁻¹¹ Wh (watt-hour)
1 eV (electron volt)	1.602 × 10 ⁻¹² erg 1.602 × 10 ⁻¹⁹ J (joule)
1 fps (foot per second)	1.097 kmph (kilometers/hour) 0.305 mps (meter/second) 0.01136 mph (mile/hour)
1 ft (foot)	30.48 cm (centimeters) 12 in. (inches) 0.3048 m (meter) 1.65 × 10 ⁻⁴ NM (nautical mile) 1.89 × 10 ⁻⁴ mi (statute mile)
1 ft ² (square foot)	2.296 × 10 ⁻⁵ ac (acre) 9.296 cm ² (square centimeters) 144 in. ² (square inches) 0.0929 m ² (square meter)
1 ft ³ (cubic foot)	28.317 cm ³ (cc, cubic centimeters) 1728 in. ³ (cubic inches) 0.0283 m ³ (cubic meter) 7.48 gal (gallons) 28.32 L (liters) 29.92 qt (quarts)
1 g (gram)	0.001 kg (kilogram) 1000 mg (milligrams) 1,000,000 ng = 10 ⁶ ng (nanograms) 2.205 × 10 ⁻³ lb (pound)
1 g/cm ³ (gram per cubic centimeter)	62.43 lb/ft ³ (pounds/cubic foot) 0.0361 lb/in. ³ (pound/cubic inch) 8.345 lb/gal (pounds/gallon)

TABLE 4.2 (continued)
Alphabetical List of Conversion Factors

Factor	Metric (SI) or English Conversions
1 gal (gallon)	3785 cm ³ (cc, cubic centimeters)
	0.134 ft ³ (cubic feet)
	231 in. ³ (cubic inches)
	3.785 L (liters)
1 Gy (gray)	1 J/kg (joule/kilogram)
	100 rad
	1 Sv (sievert), unless modified through division by an appropriate factor, such as <i>Q</i> or <i>N</i>
1 hp (horsepower)	745.7 J/sec (joules/second)
1 hr (hour)	0.0417 day
	60 min (minutes)
	3600 sec (seconds)
	5.95 × 10 ⁻³ wk (week)
	1.14 × 10 ⁻⁴ yr (year)
1 in. (inch)	2.54 cm (centimeters)
	1000 mil
1 in. ³ (cubic inch)	16.39 cm ³ (cc, cubic centimeters)
	16.39 mL (milliliters)
	5.79 × 10 ⁻⁴ ft ³ (cubic feet)
	1.64 × 10 ⁻⁵ m ³ (cubic meter)
	4.33 × 10 ⁻³ gal (gallon)
	0.0164 L (liter)
	0.55 fl oz. (fluid ounce)
1 inch of water	1.86 mmHg (millimeters of mercury)
	249.09 Pa (pascals)
	0.0361 psi (lb/in. ²)
1 j (joule)	9.48 × 10 ⁻⁴ Btu (British thermal unit)
	0.239 cal (calories)
	10,000,000 ergs = 1 × 10 ⁷ ergs
	9.87 × 10 ⁻³ L atm (liter-atmospheres)
1 kcal (kilocalorie)	1.0 N-m (newton-meter)
	3.97 Btu (British thermal units)
	1000 cal (calories)
	4186.8 J (joules)
1 kg (kilogram)	1000 g (grams)
	2205 lb (pounds)
1 km (kilometer)	3280 ft (feet)
	0.54 NM (nautical mile)
	0.6214 mi (statute mile)
1kW (kilowatt)	56.87 Btu/min (British thermal units per minute)
	1.341 hp (horsepower)
	1000 J/sec (joules per second)

TABLE 4.2 (continued)
Alphabetical List of Conversion Factors

Factor	Metric (SI) or English Conversions
1 L (liter)	1000 cm ³ (cc, cubic centimeters)
	1 dm ³ (cubic decimeter)
	0.0353 ft ³ (cubic feet)
	61.02 in. ³ (cubic inches)
	0.264 gal (gallon)
	1000 mL (milliliters)
1 lb (pound)	1.057 qt (quarts)
	453.59 g (grams)
	16 oz. (ounces)
1 lb/ft ³ (pound per cubic foot)	16.02 g/L (grams/liter)
1 lb/in. ³ (pound per cubic inch)	27.68 g/cm ³ (grams/cubic centimeter)
	1728 lb/ft ³ (pounds/cubic feet)
1 m (meter)	1 × 10 ¹⁰ Å (Ångstroms)
	100 cm (centimeters)
	3.28 ft (feet)
	39.37 in. (inches)
	1 × 10 ⁻³ km (kilometer)
	1000 mm (millimeters)
	1,000,000 μm = 1 × 10 ⁶ μm (micrometers)
	1 × 10 ⁹ nm (nanometers)
	10.76 ft ² (square feet)
1 m ² (square meter)	1550 in. ² (square inches)
1 m ³ (cubic meter)	1,000,000 cm ³ = 10 ⁶ cm ³ (cc, cubic centimeters)
	33.32 ft ³ (cubic feet)
	61,023 in. ³ (cubic inches)
	264.17 gal (gallons)
	1000 L (liters)
1 mCi (millicurie)	0.001 Ci (curie)
	3.7 × 10 ¹⁰ radioactive disintegrations/second
	3.7 × 10 ¹⁰ Bq (becquerel)
1 mi (statute mile)	5280 ft (feet)
	1.609 km (kilometers)
	1609.3 m (meters)
	0.869 NM (nautical miles)
	1760 yd (yards)
1 mi ² (square mile)	640 acres
	2.79 × 10 ⁷ ft ² (square feet)
	2.59 × 10 ⁶ m ² (square meters)
1 min (minute)	6.94 × 10 ⁻⁴ day
	0.0167 hr (hour)
	60 sec (seconds)
	9.92 × 10 ⁻⁵ wk (week)
	1.90 × 10 ⁻⁶ yr (year)

TABLE 4.2 (continued)
Alphabetical List of Conversion Factors

Factor	Metric (SI) or English Conversions
1 mmHg (mm of mercury)	1.316×10^{-3} atm (atmosphere)
	0.535 inch H ₂ O (inch of water)
	1.33 mb (millibars)
	133.32 Pa (pascals)
	1 torr
1 mph (mile per hour)	0.0193 psia (pounds/square inch absolute)
	88 fpm (feet/minute)
	1.61 kmph (kilometers/hour)
	0.447 mps (meters/second)
1 mps (meter per second)	196.9 fpm (feet/minute)
	3.6 kmph (kilometers/hour)
	2.237 mph (miles/hour)
1 N-m (newton-meter)	1.00 J (joule)
1 NM (nautical mile)	6076.1 ft (feet)
	1.852 km (kilometers)
	1.15 mi (statute miles)
	2025.4 yd (yards)
1 Pa (pascal)	9.87×10^{-6} atm (atmosphere)
	4.015×10^{-3} inch H ₂ O (inches of water)
	0.01 mb (millibar)
	7.5×10^{-3} mmHg (millimeters of mercury)
1 ppm (parts per million)	1.00 mL/m ³ (milliliter/cubic meter)
	1.00 mg/kg (milligram/kilogram)
1 psi (pounds/square inch)	0.068 atm (atmosphere)
	27.67 inch H ₂ O (inches of water)
	68.85 mb (millibars)
	51.71 mmHg (millimeters of mercury)
	6894.76 Pa (pascals)
1 qt (quart)	946.4 cm ³ (cc, cubic centimeters)
	57.75 in. ³ (cubic inches)
	0.946 L (liter)
1 rad	100 ergs/g (ergs/gram)
	0.01 Gy (gray)
	1 rem, unless modified through division by an appropriate factor, such as <i>Q</i> or <i>N</i>
1 rem	1 rad, unless modified through division by an appropriate factor, such as <i>Q</i> or <i>N</i>
1 Sv (sievert)	1 Gy, unless modified through division by an appropriate factor, such as <i>Q</i> or <i>N</i>
1 torr	1.33 mb (millibar)

TABLE 4.2 (continued)
Alphabetical List of Conversion Factors

Factor	Metric (SI) or English Conversions
1 W (watt)	3.41 Btu/hr (British thermal units/hour)
	1.341×10^{-3} hp (horsepower)
	52.18 J/sec (joules/second)
1 wk (week)	7 days
	168 hr (hours)
	10,080 min (minutes)
	6.048×10^5 sec (seconds)
	0.0192 yr (year)
1 Wh (watt-hour)	3.412 Btu (British thermal units)
	859.8 cal (calories)
	3600 J (joules)
	35.53 L-atm (liter-atmospheres)
1 yd ³ (cubic yard)	201.97 gal (gallons)
	764.55 L (liters)
1 yr (year)	365.25 day
	8766 hr (hour)
	5.26×10^5 min (minute)
	3.16×10^7 sec (second)
	52.18 wk (week)

the two lengths are given in different units. Before we can add the two lengths, we must convert one of them to the units of the other. Then, when we have two lengths in the same units, we can add them.

To perform this conversion, we need a conversion factor. In this case, we have to know how many inches make up a foot: 12 inches. Knowing this, we can perform the calculation in two steps:

- 1. 60 in. is really $60/12 = 5$ ft
- 2. 5 ft + 6 ft = 11 ft

From the example above, it can be seen that a conversion factor changes known quantities in one unit of measure to an equivalent quantity in another unit of measure. When making the conversion from one unit to another, we must know two things:

- 1. The exact number that relates the two units
- 2. Whether to multiply or divide by that number

Confusion over whether to multiply or divide is common; on the other hand, the number that relates the two units is usually known and thus is not a problem. Understanding the proper methodology—the “mechanics”—to use for various operations requires practice and common sense.

TABLE 4.3
Conversion Factors by Unit Category

Factor	Metric (SI) or English Conversions
	Units of Length
1 cm (centimeter)	0.0328 ft (foot) 0.394 in. (inch) 10,000 μm (microns, micrometers) 100,000,000 Å = 10 ⁸ Å (Ångstroms)
1 ft (foot)	30.48 cm (centimeters) 12 in. (inches) 0.3048 m (meter) 1.65 × 10 ⁻⁴ NM (nautical mile) 1.89 × 10 ⁻⁴ mi (statute mile)
1 in. (inch)	2.54 cm (centimeter) 1000 mils
1 km (kilometer)	3280.8 ft (feet) 0.54 NM (nautical mile) 0.6214 mi (statute mile)
1 m (meter)	1 × 10 ¹⁰ Å (Ångstroms) 100 cm (centimeters) 3.28 ft (feet) 39.37 in. (inches) 1 × 10 ⁻³ km (kilometer) 1000 mm (millimeters) 1,000,000 μm = 1 × 10 ⁶ μm (microns, micrometers) 1 × 10 ⁹ nm (nanometers)
1 NM (nautical mile)	6076.1 ft (feet) 1.852 km (kilometers) 1.15 mi (statute miles) 2025.4 yd (yards)
1 mi (statute mile)	5280 ft (feet) 1.609 km (kilometers) 1690.3 m (meters) 0.869 NM (nautical mile) 1760 yd (yards)
	Units of Area
1 cm ² (square centimeter)	1.076 × 10 ⁻³ ft ² (square feet) 0.155 in. ² (square inch) 1 × 10 ⁻⁴ m ² (square meter)
1 ft ² (square foot)	2.296 × 10 ⁻⁵ ac (acre) 929.03 cm ² (square centimeters) 144 in. ² (square inches) 0.0929 m ² (square meter)
1 m ² (square meter)	10.76 ft ² (square feet) 1550 in. ² (square inches)

TABLE 4.3 (continued)
Conversion Factors by Unit Category

Factor	Metric (SI) or English Conversions
1 mi ² (square mile)	640 acres
	2.79 × 10 ⁷ ft ² (square feet)
	2.59 × 10 ⁶ m ² (square meter)
Units of Volume	
1 cm ³ (cubic centimeter)	3.53 × 10 ⁻⁵ ft ³ (cubic feet)
	0.061 in. ³ (cubic inch)
	2.64 × 10 ⁻⁴ gal (gallon)
	0.001 L (liter)
1 ft ³ (cubic foot)	1.00 mL (milliliter)
	28,317 cm ³ (cc, cubic centimeters)
	1728 in. ³ (cubic inches)
	0.0283 m ³ (cubic meter)
	7.48 gal (gallons)
1 in. ³ (cubic inch)	28.32 L (liters)
	29.92 qt (quarts)
	16.39 cm ³ (cc, cubic centimeters)
	16.39 mL (milliliters)
	5.79 × 10 ⁻⁴ ft ³ (cubic feet)
	1.64 × 10 ⁻⁵ m ³ (cubic meter)
	4.33 × 10 ⁻³ gal (gallon)
1 m ³ (cubic meter)	0.0164 L (liter)
	1,000,000 cm ³ = 10 ⁶ cm ³ (cc, cubic centimeters)
	35.31 ft ³ (cubic feet)
	61,023 in. ³ (cubic inches)
	264.17 gal (gallons)
1 yd ³ (cubic yard)	1000 L (liters)
	201.97 gal (gallons)
	764.55 L (liters)
1 gal (gallon)	3785 cm ³ (cc, cubic centimeters)
	0.134 ft ³ (cubic feet)
	231 in. ³ (cubic inches)
	3.785 L (liters)
1 L (liter)	1000 cm ³ (cc, cubic centimeters)
	1 dm ³ (cubic decimeter)
	0.0353 ft ³ (cubic feet)
	61.02 in. ³ (cubic inches)
	0.264 gal (gallon)
	1000 mL (milliliters)
1 qt (quart)	1.057 qt (quarts)
	946.4 cm ³ (cc, cubic centimeters)
	57.75 in. ³ (cubic inches)
	0.946 L (liter)

TABLE 4.3 (continued)
Conversion Factors by Unit Category

Factor	Metric (SI) or English Conversions
	Units of Mass
1 g (gram)	0.001 kg (kilogram) 1000 mg (milligrams) 1,000,000 mg = 10 ⁶ ng (nanograms) 2.205 × 10 ⁻³ lb (pounds) 15.43 gr (grains) 8.99 × 10 ¹³ J (joules)
1 kg (kilogram)	1000 g (grams) 2.205 lb (pounds)
1 lb (pound)	453.59 g (grams) 0.45359 kg (kilogram) 16 oz. (ounces)
	Units of Time
1 day	24 hr (hours) 1440 min (minutes) 86,400 sec (seconds) 0.143 wk (week) 2.738 × 10 ⁻³ yr (year)
1 hr (hour)	0.0417 day 60 min (minutes) 3600 sec (seconds) 5.95 × 10 ⁻³ wk (week) 1.14 × 10 ⁻⁴ yr (year)
1 min (minute)	6.94 × 10 ⁻⁴ day 0.0167 hr (hour) 60 sec (seconds) 9.92 × 10 ⁻⁵ wk (week) 1.90 × 10 ⁻⁶ yr (year)
1 wk (week)	7 days 168 hr (hours) 10,080 min (minutes) 6.048 × 10 ⁵ sec (seconds) 0.0192 yr (year)
1 yr (year)	365.25 days 8766 hr (hours) 5.26 × 10 ⁵ min (minutes) 3.16 × 10 ⁷ sec (seconds) 52.18 wk (weeks)

TABLE 4.3 (continued)
Conversion Factors by Unit Category

Factor	Metric (SI) or English Conversions
Units of the Measure of Temperature	
°C	$(5/9)[(°F) - 32°]$
1°C (expressed as an interval)	$33.8°F = (9/5)(°F)$
	1.8°R (degrees Rankine)
	1.0 K (degree Kelvin)
°F Fahrenheit)	$(9/5)[(°C) + 32°]$
1°F (expressed as an interval)	$0.556°C = (5/9)°C$
	1.0°R (degree Rankine)
	0.556 K (degree Kelvin)
Units of Force	
1 dyne	1×10^{-5} N (newton)
1 N (newton)	1×10^5 dyne
Units of Work or Energy	
1 Btu (British thermal unit)	252 cal (calories)
	1055.06 J (joules)
	10.41 L-atm (liter-atmospheres)
	0.293 Wh (watt-hour)
1 cal (calorie)	3.97×10^{-3} Btu (British thermal unit)
	4.18 J (joules)
	0.0413 L-atm (liter-atmosphere)
	1.163×10^{-3} Wh (watt-hour)
1 eV (electron volt)	1.602×10^{-12} erg
	1.602×10^{-19} J (joule)
1 erg	1 dyne-centimeter
	1×10^{-7} J (joule)
	2.78×10^{-11} Wh (watt-hour)
1 J (joule)	9.48×10^{-4} Btus (British thermal unit)
	0.239 cal (calorie)
	10,000,000 ergs = 1×10^7 ergs
	9.87×10^{-3} L-atm (liter-atmosphere)
	1.00 N-m (newton-meter)
1 kcal (kilocalorie)	3.97 Btu (British thermal unit)
	1000 cal (calories)
	4186.8 J (joules)
1 kWh (kilowatt-hour)	3412.14 Btu (British thermal units)
	3.6×10^6 J (joules)
	859.8 kcal (kilocalories)

TABLE 4.3 (continued)
Conversion Factors by Unit Category

Factor	Metric (SI) or English Conversions
1 N-m (newton-meter)	1.00 J (joule)
	2.78 × 10 ⁻⁴ Wh (watt-hour)
1 Wh (watt-hour)	3.412 Btu (British thermal units)
	859.8 cal (calories)
	3600 J (joules)
	35.53 L-atm (liter-atmospheres)
Units of Power	
1 hp (horsepower)	745.7 J/sec (joules/second)
1 kW (kilowatt)	56.87 Btu/min (British thermal units/minute)
	1.341 hp (horsepower)
	1000 J/sec (joules/second)
1 W (watt)	3.41 Btu/hr (British thermal units/hour)
	1.341 × 10 ⁻³ hp (horsepower)
	1.00 J/sec (joules/second)
Units of Pressure	
1 atm (atmosphere)	1.013 bars
	10.133 N/cm ² (newtons/square centimeter)
	33.90 ft H ₂ O (feet of water)
	101.325 kPa (kilopascals)
	14.70 psia (pounds per square inch absolute)
	760 torr
	760 mmHg (millimeters of mercury)
1 bar	0.987 atm (atmosphere)
	1 × 10 ⁶ dynes/cm ² (dynes/square centimeter)
	33.45 ft H ₂ O (feet of water)
	1 × 10 ⁵ Pa (pascal)
	750.06 torr
	750.06 mmHg (millimeters of mercury)
1 inch of water	1.86 mmHg (millimeters of mercury)
	249.09 Pa (pascals)
	0.0361 psi (lb/in. ²)
1 mmHg (millimeter of mercury)	1.316 × 10 ⁻³ atm (atmosphere)
	0.535 in H ₂ O (inches of water)
	1.33 mb (millibars)
	133.32 Pa (pascals)
	1 torr
	0.0193 psia (pounds per square inch absolute)

TABLE 4.3 (continued)
Conversion Factors by Unit Category

Factor	Metric (SI) or English Conversions
1 pascal	9.87×10^{-6} atm (atmosphere)
	4.015×10^{-3} inch H ₂ O (inches of water)
	0.01 mb (millibar)
	7.5×10^{-3} mmHg (millimeters of mercury)
1 psi (pounds per square inch)	0.068 atm (atmosphere)
	27.67 inch H ₂ O (inches of water)
	68.85 mb (millibars)
	51.71 mmHg (millimeters of mercury)
1 torr	6894.76 Pa (pascals)
	1.33 mb (millibars)

Units of Velocity or Speed

1 fps (foot per second)	1.097 kmph (kilometers/hour)
	0.305 mps (meters/second)
	0.01136 mph (miles/hour)
1 mps (meters per second)	196.9 fpm (feet/minute)
	3.6 kmph (kilometers/hour)
	2.237 mph (miles/hour)
1 mph (miles per hour)	88 fpm (feet/minute)
	1.61 kmph (kilometers/hour)
	0.447 mps (meters/second)

Units of Density

1 g/cm ³ (grams per cubic centimeter)	62.43 lb/ft ³ (pounds/cubic foot)
	0.0361 lb/in. ³ (pound/cubic inch)
	8.345 lb/gal (pounds/gallon)
1 lb/ft ³ (pounds/cubic foot)	16.02 g/L (grams/liter)
1 lb/in. ² (pounds/cubic inch)	27.68 g/cm ³ (grams/cubic centimeter)
	1.728 lb/ft ³ (pounds/cubic foot)

Units of Concentration

1 ppm (parts/million-volume)	1.00 mL/m ³ (milliliter/cubic meter)
1 ppm (wt)	1.00 mg/kg (milligram/kilogram)

Radiation and Dose Related Units

1 Bq (becquerel)	1 radioactive disintegration/second
	2.7×10^{-11} Ci (curie)
	2.7×10^{-8} (millicurie)
1 Ci (curie)	3.7×10^{10} radioactive disintegrations/second
	3.7×10^{10} Bq (becquerels)
	1000 mCi (millicuries)

TABLE 4.3 (continued)
Conversion Factors by Unit Category

Factor	Metric (SI) or English Conversions
1 Gy (gray)	1 J/kg (joule/kilogram) 100 rad 1 Sv, unless modified through division by an appropriate factor, such as <i>Q</i> or <i>N</i>
1 mCi (millicurie)	0.001 Ci (curie) 3.7×10^{10} radioactive disintegrations/second 3.7×10^{10} Bq (becquerels)
1 rad	100 ergs/g (ergs/gram) 0.01 Gy (gray) 1 rem, unless modified through division by an appropriate factor, such as <i>Q</i> or <i>N</i>
1 rem	1 rad, unless modified through division by an appropriate factor, such as <i>Q</i> or <i>N</i>
1 Sv (sievert)	1 Gy, unless modified through division by an appropriate factor, such as <i>Q</i> or <i>N</i>

Along with using the proper mechanics (and practice and common sense) to make conversions, probably the easiest and fastest method of converting units is to use a conversion table. The simplest conversion requires that the measurement be multiplied or divided by a constant value. For instance, if the depth of wet cement in a form is 0.85 ft, multiplying by 12 inches per foot converts the measured depth to inches (10.2 inches). Likewise, if the depth of the cement in the form is measured as 16 inches, dividing by 12 inches per foot converts the depth measurement to feet (1.33 feet).

4.3.1.1 Weight, Concentration, and Flow

Using Table 4.4 to convert from one unit expression to another and *vice versa* is good practice; however, when making conversions to solve process computations in water treatment operations, for example, we must be familiar with conversion calculations based on a relationship between weight, flow or volume, and concentration. The basic relationship is

$$\text{Weight} = \text{Concentration} \times (\text{Flow or Volume}) \times \text{Factor} \tag{4.1}$$

Table 4.5 summarizes weight, volume, and concentration calculations. With practice, many of these calculations become second nature to users.

The following conversion factors are used extensively in environmental engineering (e.g., water and wastewater operations):

TABLE 4.4
Conversion Table

To Convert	Multiply by	To Get
Feet	12	Inches
Yards	3	Feet
Yards	36	Inches
Inches	2.54	Centimeters
Meters	3.3	Feet
Meters	100	Centimeters
Meters	1000	Millimeters
Square yards	9	Square feet
Square feet	144	Square inches
Acres	43,560	Square feet
Cubic yards	27	Cubic feet
Cubic feet	1728	Cubic inches
Cubic feet (water)	7.48	Gallons
Cubic feet (water)	62.4	Pounds
Acre-feet	43,560	Cubic feet
Gallons (water)	8.34	Pounds
Gallons (water)	3.785	Liters
Gallons (water)	3785	Milliliters
Gallons (water)	3785	Cubic centimeters
Gallons (water)	3785	Grams
Liters	1000	Milliliters
Days	24	Hours
Days	1440	Minutes
Days	86,400	Seconds
Million gallons/day	1,000,000	Gallons/day
Million gallons/day	1.55	Cubic feet/second
Million gallons/day	3.069	Acre-feet/day
Million gallons/day	36.8	Acre-inches/day
Million gallons/day	3785	Cubic meters/day
Gallons/minute	1440	Gallons/day
Gallons/minute	63.08	Liters/minute
Pounds	454	Grams
Grams	1000	Milligrams
Pressure (psi)	2.31	Head (feet of water)
Horsepower	33,000	Foot-pounds/minute
Horsepower	0.746	Kilowatts

- 7.48 gallons = 1 cubic foot (ft³)
- 3.785 liters = 1 gallon
- 454 grams = 1 pound
- 1000 milliliters = 1 liter
- 1000 milligrams = 1 gram
- 1 ft³/sec (cfs) = 0.6465 MGD

TABLE 4.5
Weight, Volume, and Concentration Calculations

To Calculate	Formula
Pounds	Concentration (mg/L) × Tank Volume (MG) × 8.34 lb/MG/mg/L
Pounds/day	Concentration (mg/L) × Flow (MGD) × 8.34 lb/MG/mg/L
Million gallons/day	$\frac{\text{Quantity (lb/day)}}{\text{Concentration (mg/L)} \times 8.34 \text{ lb/MG/mg/L}}$
Milligrams/liter	$\frac{\text{Quantity (lb)}}{\text{Tank volume (MG)} \times 8.34 \text{ lb/MG/mg/L}}$
Kilograms/liter	Concentration (mg/L) × Volume (MG) × 3.785 L/gal
Kilograms/day	Concentration (mg/L) × Flow (MGD) × 3.785 L/gal
Pounds/dry ton	Concentration (mg/kg) × 0.002 lb/dry ton/mg/kg

Note: *Density* (also called *specific weight*) is mass per unit volume and may be written as lb/ft³, lb/gal, g/mL, or g/m³. If we take a fixed-volume container, fill it with a fluid, and weigh it, we can determine the density of the fluid by subtracting the weight of the container.

- 1 gallon of water weighs 8.34 pounds; the density is 8.34 lb/gal
- 1 milliliter of water weighs 1 gram; the density is 1 g/mL
- 1 cubic foot of water weighs 62.4 pounds; the density is 62.4 lb/gal
- 8.34 lb/gal = milligrams per liter, which is used to convert dosage in mg/L into lb/day/MGD (e.g., 1 mg/L × 10 MGD × 8.34 lb/gal = 83.4 lb/day)
- 1 psi = 2.31 feet of water (head)
- 1 foot head = 0.433 psi
- °F = 9/5(°C + 32)
- °C = 5/9(°F – 32)
- Average water usage, 100 gallons/capita/day (gpcd)
- Persons per single family residence, 3.7

4.3.1.2 Wastewater Conversion Examples

Use Tables 4.4 and 4.5 to make the conversions necessary in the following example problems. Other conversions are presented in appropriate sections of the text.

■ EXAMPLE 4.4

Convert cubic feet to gallons.

$$\text{Gallons} = \text{Cubic feet (ft}^3\text{)} \times \text{gal/ft}^3$$

Problem: How many gallons of biosolids can be pumped to a digester that has 3600 ft³ of volume available?

Solution:

$$\text{Gallons} = 3600 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 26,928 \text{ gal}$$

■ EXAMPLE 4.5

Convert gallons to cubic feet.

$$\text{Cubic feet (ft}^3\text{)} = \frac{\text{Gallons}}{7.48 \text{ gal/ft}^3}$$

Problem: How many cubic feet of biosolids are removed when 18,200 gal are withdrawn?

Solution:

$$\text{Cubic feet} = \frac{18,200 \text{ gal}}{7.48 \text{ gal/ft}^3} = 2433 \text{ ft}^3$$

■ EXAMPLE 4.6

Convert gallons to pounds.

$$\text{Pounds (lb)} = \text{Gallons} \times 8.34 \text{ lb/gal}$$

Problem: If 1650 gal of solids are removed from the primary settling tank, how many pounds of solids are removed?

Solution:

$$\text{Pounds} = 1650 \text{ gal} \times 8.34 \text{ lb/gal} = 13,761 \text{ lb}$$

■ EXAMPLE 4.7

Convert pounds to gallons.

$$\text{Gallons (gal)} = \frac{\text{Pounds (lb)}}{8.34 \text{ lb/gal}}$$

Problem: How many gallons of water are required to fill a tank that holds 7540 lb of water?

Solution:

$$\text{Gallons} = \frac{7540 \text{ lb}}{8.34 \text{ lb/gal}} = 904 \text{ gal}$$

■ EXAMPLE 4.8

Convert milligrams per liter to pounds.

$$\text{Pounds} = \text{Concentration (mg/L)} \times \text{Volume (MG)} \times 8.34 \text{ lb/MG/mg/L}$$

Key Point: For plant operations, concentrations in milligrams per liter or parts per million determined by laboratory testing must be converted to quantities of pounds, kilograms, pound per day, or kilograms per day.

Problem: The solids concentration in the aeration tank is 2580 mg/L. The aeration tank volume is 0.95 MG. How many pounds of solids are in the tank?

Solution:

$$\text{Pounds} = 2580 \text{ mg/L} \times 0.95 \text{ MG} \times 8.34 \text{ lb/MG/mg/L} = 20,441.3 \text{ lb}$$

■ EXAMPLE 4.9

Convert milligrams per liter to pounds per day.

$$\text{Pounds/day} = \text{Concentration (mg/L)} \times \text{Flow (MGD)} \times 8.34 \text{ lb/MG/mg/L}$$

Problem: How many pounds of solids are discharged per day when the plant effluent flow rate is 4.75 MGD and the effluent solids concentration is 26 mg/L?

Solution:

$$\text{Pounds/day} = 26 \text{ mg/L} \times 4.75 \text{ MGD} \times 8.34 \text{ lb/MG/mg/L} = 1030 \text{ lb/day}$$

■ EXAMPLE 4.10

Convert milligrams per liter to kilograms per day.

$$\text{Kilograms/day} = \text{Concentration (mg/L)} \times \text{Volume (MG)} \times 3.785 \text{ L/gal}$$

Problem: The effluent contains 26 mg/L of BOD₅. How many kilograms per day of BOD₅ are discharged when the effluent flow rate is 9.5 MGD?

Solution:

$$\text{Kilograms/day} = 26 \text{ mg/L} \times 9.5 \text{ MG} \times 3.785 \text{ L/gal} = 934 \text{ kg/day}$$

■ EXAMPLE 4.11

Convert pounds to milligrams per liter.

$$\text{Concentration (mg/L)} = \frac{\text{Quantity (lb)}}{\text{Volume (MG)} \times 8.34 \text{ lb/MG/mg/L}}$$

Problem: An aeration tank contains 89,990 pounds of solids. The volume of the aeration tank is 4.45 MG. What is the concentration of solids in the aeration tank in milligrams per liter?

Solution:

$$\text{Concentration} = \frac{89,990 \text{ lb}}{4.45 \text{ MG} \times 8.34 \text{ lb/MG/mg/L}} = 2425 \text{ mg/L}$$

■ EXAMPLE 4.12

Convert pounds per day to milligrams per liter.

$$\text{Concentration (mg/L)} = \frac{\text{Quantity (lb/day)}}{\text{Volume (MGD)} \times 8.34 \text{ lb/MG/mg/L}}$$

Problem: The disinfection process uses 4820 pounds per day of chlorine to disinfect a flow of 25.2 MGD. What is the concentration of chlorine applied to the effluent?

Solution:

$$\text{Concentration} = \frac{4820 \text{ lb/day}}{25.2 \text{ MGD} \times 8.34 \text{ lb/MG/mg/L}} = 22.9 \text{ mg/L}$$

■ EXAMPLE 4.13

Convert pounds to flow in million gallons per day.

$$\text{Flow (MGD)} = \frac{\text{Quantity (lb/day)}}{\text{Concentration (mg/L)} \times 8.34 \text{ lb/MG/mg/L}}$$

Problem: 9640 pounds of solids must be removed from the activated biosolids process per day. The waste activated biosolids concentration is 7699 mg/L. How many million gallons per day of waste activated biosolids must be removed?

Solution:

$$\text{Flow} = \frac{9640 \text{ lb/day}}{7699 \text{ mg/L} \times 8.34 \text{ lb/MG/mg/L}} = 0.15 \text{ MGD}$$

■ EXAMPLE 4.14

Convert million gallons per day (MGD) to gallons per minute (gpm).

$$\text{Flow (gpm)} = \frac{\text{Flow (MGD)} \times 1,000,000 \text{ gal/MG}}{1440 \text{ min/day}}$$

Problem: The current flow rate is 5.55 MGD. What is the flow rate in gallons per minute?

Solution:

$$\text{Flow} = \frac{5.55 \text{ MGD} \times 1,000,000 \text{ gal/MG}}{1440 \text{ min/day}} = 3854 \text{ gpm}$$

■ EXAMPLE 4.15

Convert million gallons per day (MGD) to gallons per day (gpd).

$$\text{Flow (gpd)} = \text{Flow (MGD)} \times 1,000,000 \text{ gal/MG}$$

Problem: The influent meter reads 28.8 MGD. What is the current flow rate in gallons per day?

Solution:

$$\text{Flow} = 28.8 \text{ MGD} \times 1,000,000 \text{ gal/MG} = 28,800,000 \text{ gpd}$$

■ EXAMPLE 4.16

Convert million gallons per day (MGD) to cubic feet per second (cfs).

$$\text{Flow (cfs)} = \text{Flow (MGD)} \times 1.55 \text{ cfs/MGD}$$

Problem: The flow rate entering the grit channel is 2.89 MGD. What is the flow rate in cubic feet per second?

Solution:

$$\text{Flow} = 2.89 \text{ MGD} \times 1.55 \text{ cfs/MGD} = 4.48 \text{ cfs}$$

■ EXAMPLE 4.17

Convert gallons per minute (gpm) to million gallons per day (MGD).

$$\text{Flow (MGD)} = \frac{\text{Flow (gpm)} \times 1440 \text{ min/day}}{1,000,000 \text{ gal/MG}}$$

Problem: The flow meter indicates that the current flow rate is 1469 gpm. What is the flow rate in million gallons per day?

Solution:

$$\text{Flow} = \frac{1469 \text{ gpm} \times 1440 \text{ min/day}}{1,000,000 \text{ gal/MG}} = 2.12 \text{ MGD (rounded)}$$

■ EXAMPLE 4.18

Convert gallons per day (gpd) to million gallons per day (MGD).

$$\text{Flow (MGD)} = \frac{\text{Flow (gal/day)}}{1,000,000 \text{ gal/MG}}$$

Problem: The totalizing flow meter indicates that 33,444,950 gal of wastewater have entered the plant in the past 24 hr. What is the flow rate in million gallons per day?

Solution:

$$\text{Flow} = \frac{33,444,950 \text{ gal/day}}{1,000,000 \text{ gal/MG}} = 33.44 \text{ MGD}$$

■ EXAMPLE 4.19

Convert flow in cubic feet per second (cfs) to million gallons per day (MGD).

$$\text{Flow (MGD)} = \frac{\text{Flow (cfs)}}{1.55 \text{ cfs/MG}}$$

Problem: The flow in a channel is determined to be 3.89 cubic feet per second (cfs). What is the flow rate in million gallons per day (MGD)?

Solution:

$$\text{Flow} = \frac{3.89 \text{ cfs}}{1.55 \text{ cfs/MG}} = 2.5 \text{ MGD}$$

■ EXAMPLE 4.20

Problem: The water in a tank weighs 675 lb. How many gallons does it hold?

Solution: Water weighs 8.34 lb/gal; therefore,

$$\frac{675 \text{ lb}}{8.34 \text{ lb/gal}} = 80.9 \text{ gal}$$

■ EXAMPLE 4.21

Problem: A liquid chemical weighs 62 lb/ft³. How much does a 5-gal can of it weigh?

Solution: Solve for specific gravity, determine lb/gal, and multiply by 5:

$$\text{Specific gravity} = \frac{\text{Weight of chemical (lb/ft}^3\text{)}}{\text{Weight of water (lb/ft}^3\text{)}} = \frac{62 \text{ lb/ft}^3}{62.4 \text{ lb/ft}^3} = 0.99$$

$$0.99 = \frac{\text{Weight of chemical (lb/gal)}}{8.34 \text{ lb/gal}}$$

$$\text{Weight of chemical} = 8.26 \text{ lb/gal}$$

$$8.26 \text{ lb/gal} \times 5 \text{ gal} = 41.3 \text{ lb}$$

■ EXAMPLE 4.22

Problem: A wooden piling with a diameter of 16 in. and a length of 16 ft weighs 50 lb/ft³. If it is inserted vertically into a body of water, what vertical force is required to hold it below the water surface?

Solution: If this piling had the same weight as water, it would rest just barely submerged. Find the difference between its weight and that of the same volume of water—that is the weight required to keep it down:

$$62.4 \text{ lb/ft}^3 \text{ (water)} - 50.0 \text{ lb/ft}^3 \text{ (piling)} = 12.4 \text{ lb/ft}^3$$

$$\text{Volume of piling} = 0.785 \times (1.33)^2 \times 16 \text{ ft} = 22.21 \text{ ft}^3$$

$$12.4 \text{ lb/ft}^3 \times 22.21 \text{ ft}^3 = 275.4 \text{ lb}$$

■ EXAMPLE 4.23

Problem: A liquid chemical with a specific gravity (SG) of 1.22 is pumped at a rate of 40 gpm. How many pounds per day are being delivered by the pump?

Solution: Solve for pounds pumped per minute, then change to pounds/day.

$$8.34 \text{ lb/gal water} \times 1.22 \text{ SG liquid chemical} = 10.2 \text{ lb/gal liquid}$$

$$40 \text{ gal/min} \times 10.2 \text{ lb/gal} = 408 \text{ lb/min}$$

$$408 \text{ lb/min} \times 1440 \text{ min/day} = 587,520 \text{ lb/day}$$

■ EXAMPLE 4.24

Problem: A cinder block weighs 70 lb in air. When immersed in water, it weighs 40 lb. What are the volume and specific gravity of the cinder block?

Solution: The cinder block displaces 30 lb of water; solve for cubic feet of water displaced (equivalent to volume of cinder block).

$$\frac{30 \text{ lb water displaced}}{62.4 \text{ lb/ft}^3} = 0.48 \text{ ft}^3 \text{ water displaced}$$

The cinder block volume is 0.48 ft³, which weighs 70 lb; thus,

$$\frac{70 \text{ lb}}{0.48 \text{ ft}^3} = 145.8 \text{ lb/ft}^3 \text{ density of cinder block}$$

$$\text{Specific gravity} = \frac{\text{Density of cinder block}}{\text{Density of water}} = \frac{145.8 \text{ lb/ft}^3}{62.4 \text{ lb/ft}^3} = 2.34$$

4.3.1.3 Temperature Conversions

Two commonly used methods used to make temperature conversions. We have already demonstrated the following methods:

- $^{\circ}\text{C} = 5/9(^{\circ}\text{F} - 32)$
- $^{\circ}\text{F} = 9/5(^{\circ}\text{C}) + 32$

■ EXAMPLE 4.25

Problem: At a temperature of 4°C , water is at its greatest density. What is that temperature in degrees Fahrenheit?

Solution:

$$9/5(^{\circ}\text{C}) + 32 = 9/5(4) + 32 = 7.2 + 32 = 39.2^{\circ}\text{F}$$

The difficulty arises when one tries to recall these formulas from memory. Probably the easiest way to recall these important formulas is to remember these basic steps for both Fahrenheit and Celsius conversions:

1. Add 40° .
2. Multiply by the appropriate fraction ($5/9$ or $9/5$).
3. Subtract 40° .

Obviously, the only variable in this method is the choice of $5/9$ or $9/5$ in the multiplication step. To make the proper choice, you must be familiar with the two scales. The freezing point of water is 32° on the Fahrenheit scale and 0° on the Celsius scale. The boiling point of water is 212° on the Fahrenheit scale and 100° on the Celsius scale.

Note: At the same temperature, higher numbers are associated with the Fahrenheit scale and lower numbers with the Celsius scale. This important relationship helps you decide whether to multiply by $5/9$ or $9/5$.

Now look at a few conversion problems to see how the three-step process works.

■ EXAMPLE 4.26

Problem: Suppose that we wish to convert 240°F to Celsius.

Solution: Using the three-step process, we proceed as follows:

1. Add 40°

$$240^{\circ} + 40^{\circ} = 280^{\circ}$$

2. 280° must be multiplied by either $5/9$ or $9/5$. Because the conversion is to the Celsius scale, we will be moving to a number *smaller* than 280. Through reason and observation, obviously, if 280 were multiplied by $9/5$, the result would be almost the same as multiplying by 2, which would double 280 rather than make it smaller. If we multiply by $5/9$, the result will be about

the same as multiplying by $1/2$, which would cut 280 in half. Because in this problem we wish to move to a smaller number, we should multiply by $5/9$:

$$(5/9)(280^\circ) = 156.0^\circ\text{C}$$

3. Now subtract 40° .

$$156^\circ\text{C} - 40^\circ\text{C} = 116^\circ\text{C}$$

Therefore, $240^\circ\text{F} = 116^\circ\text{C}$.

■ EXAMPLE 4.27

Problem: Convert 22°C to Fahrenheit.

Solution:

1. Add 40° :

$$22^\circ + 40^\circ = 62^\circ$$

2. Because we are converting from Celsius to Fahrenheit, we are moving from a smaller to a larger number, and $9/5$ should be used in the multiplications:

$$(9/5)(62^\circ) = 112^\circ$$

3. Subtract 40:

$$112^\circ - 40^\circ = 72^\circ$$

Thus, $22^\circ\text{C} = 72^\circ\text{F}$.

Obviously, knowing how to make these temperature conversion calculations is useful, but it is generally more practical to use a temperature conversion table.

4.4 GENERAL TREATMENT POND PARAMETERS

Before discussing the process control calculations mentioned earlier, it is important to first describe the calculations for determining the area, volume, and flow rate parameters that are crucial in making treatment pond calculations.

- Determining pond area in acres

$$\text{Area (ac)} = \text{Area (ft}^2\text{)}/43,560 \text{ ft}^2/\text{ac} \quad (4.2)$$

- Determining pond volume in acre-feet

$$\text{Volume (ac-ft)} = \text{Volume (ft}^3\text{)}/43,560 \text{ ft}^2/\text{ac-ft} \quad (4.3)$$

- Determining flow rate in acre-feet/day

$$\text{Flow (ac-ft/day)} = \text{Flow (MGD)} \times 3069 \text{ ac-ft/MG} \quad (4.4)$$

Key Point: Acre-feet (ac-ft) is a unit that can cause confusion, especially for those not familiar with pond or lagoon operations. One ac-ft is the volume of a box with a 1-ac top and 1 ft of depth—but the top does not have to be an even number of acres in size to use ac-ft.

- Determining flow rate in acre-inches/day

$$\text{Flow (ac-in./day)} = \text{Flow (MGD)} \times 36.8 \text{ ac-in./MG} \quad (4.5)$$

4.5 TREATMENT POND PROCESS CONTROL CALCULATIONS

Although there are no recommended process control calculations for the treatment pond, several calculations may be helpful in evaluating process performance or identifying causes of poor performance. These include hydraulic detention time, BOD loading, organic loading rate, BOD removal efficiency, population loading, and hydraulic loading rate. In the following, we provide a few calculations that might be helpful in pond performance evaluation and identification of causes of poor process performance along with other calculations and equations that may be helpful.

4.5.1 HYDRAULIC DETENTION TIME (DAYS)

$$\text{Hydraulic detention time (days)} = \frac{\text{Pond volume (ac-ft)}}{\text{Influent flow (ac-ft/day)}} \quad (4.6)$$

Key Point: Hydraulic detention times for stabilization ponds normally range from 30 to 120 days.

■ EXAMPLE 4.28

Problem: A stabilization pond has a volume of 54.5 ac-ft. What is the detention time in days when the flow is 0.35 MGD?

Solution:

$$\text{Flow} = 0.35 \text{ MGD} \times 3069 \text{ ac-ft/MG} = 1.07 \text{ ac-ft/day}$$

$$\text{Detention time} = \frac{54.5 \text{ ac-ft}}{1.07 \text{ ac-ft/day}} = 51 \text{ days}$$

4.5.2 BOD LOADING

When calculating BOD loading on a wastewater treatment pond, the following equation is used:

$$\text{BOD (lb/day)} = \text{BOD (mg/L)} \times \text{Flow (MGD)} \times 8.34 \text{ lb/gal} \quad (4.7)$$

■ EXAMPLE 4.29

Problem: Calculate the BOD loading (lb/day) on a pond if the influent flow is 0.3 MGD with a BOD of 200 mg/L.

Solution:

$$\text{BOD} = \text{BOD} \times \text{Flow} \times 8.34 \text{ lb/gal} = 200 \text{ mg/L} \times 0.3 \text{ MGD} \times 8.34 \text{ lb/gal} = 500 \text{ lb/day}$$

4.5.3 ORGANIC LOADING RATE

Organic loading can be expressed as pound of BOD per acre per day (most common), pounds of BOD per acre-foot per day, or people per acre per day.

$$\text{Organic loading rate (lb BOD/ac/day)} = \frac{\text{BOD (mg/L)} \times \text{Influent flow (MGD)} \times 8.34 \text{ lb/gal}}{\text{Pond area (ac)}} \quad (4.8)$$

Key Point: The organic loading rate normally ranges from 10 to 50 lb BOD per day per acre.

■ EXAMPLE 4.30

Problem: A wastewater treatment pond has an average width of 370 ft and an average length of 730 ft. The influent flow rate to the pond is 0.10 MGD with a BOD concentration of 165 mg/L. What is the organic loading rate to the pond in pounds per day per acre (lb/day/ac)?

Solution:

$$730 \text{ ft} \times 370 \text{ ft} \times \frac{1 \text{ ac}}{43,560 \text{ ft}^2} = 6.2 \text{ ac}$$

$$0.10 \text{ MGD} \times 165 \text{ mg/L} \times 8.34 \text{ lb/gal} = 138 \text{ lb/day}$$

$$\text{Organic loading rate} = \frac{138 \text{ lb/day}}{6.2 \text{ ac}} = 22.3 \text{ lb/day/ac}$$

4.5.4 BOD REMOVAL EFFICIENCY

The efficiency of any treatment process is its effectiveness in removing various constituents from the water or wastewater. BOD removal efficiency is therefore a measure of the effectiveness of the wastewater treatment pond in removing BOD from the wastewater.

$$\% \text{ BOD removed} = \frac{\text{BOD removed (mg/L)}}{\text{BOD total (mg/L)}} \times 100$$

■ EXAMPLE 4.3I

Problem: The BOD entering a waste treatment pond is 194 mg/L. If the BOD in the pond effluent is 45 mg/L, what is the BOD removal efficiency of the pond?

Solution:

$$\% \text{ BOD removed} = \frac{\text{BOD removed (mg/L)}}{\text{BOD total (mg/L)}} \times 100 = \frac{149 \text{ mg/L}}{194 \text{ mg/L}} \times 100 = 77\%$$

4.5.5 POPULATION LOADING

$$\text{Population loading (people/ac/day)} = \frac{\text{BOD (mg/L)} \times \text{Influent flow (MGD)} \times 8.34 \text{ lb/gal}}{\text{Pond area (ac)}} \quad (4.9)$$

4.5.6 HYDRAULIC LOADING OR OVERFLOW RATE (INCHES/DAY)

$$\text{Hydraulic loading (in./day)} = \frac{\text{Influent flow (ac-in./day)}}{\text{Pond area (ac)}} \quad (4.10)$$

4.6 AERATED PONDS

Depending on the hydraulic retention time, the effluent from an aerated pond will contain from one-third to one-half the concentration of the influent BOD in the form of cell tissue (Metcalf & Eddy, 1991). These solids must be removed by settling before the effluent is discharged. The mathematical relationship for BOD removal in a complete mix activated sludge pond is derived from the following equation:

$$QS_o - QS - kSV = 0 \quad (4.11)$$

Rearranged:

$$\frac{S}{S_o} = \frac{1}{1 + k(V/Q)} = \frac{\text{Effluent BOD}}{\text{Influent BOD}} \quad (4.12)$$

$$= \frac{1}{1 + k\theta} \quad (4.13)$$

where

S = Effluent BOD concentration (mg/L).

S_o = Influent BOD concentration (mg/L).

k = Overall first-order BOD removal rate (per day).
 Q = Wastewater flow (m³/day, MGD).
 θ = Hydraulic retention time (days).

The temperature in the aerated pond resulting from the influent wastewater temperature, air temperature, surface area, and flow can be computed using the following equation (Mancini and Barnhart, 1968):

$$T_i - T_w = \frac{(T_w - T_a) f A}{Q} \quad (4.14)$$

where

T_i = Influent wastewater temperature (°C, °F).
 T_w = Lagoon water temperature (°C, °F).
 T_a = Ambient air temperature (°C, °F).
 f = Proportionality factor = 12×10^{-6} (British system) or 0.5 (SI units).
 A = Surface area of lagoon (m², ft²).
 Q = Wastewater flow (m³/day, MGD).

With Equation 4.14 rearranged, the pond water temperature is

$$T_w = \frac{AfT_a + QT_i}{Af + Q} \quad (4.15)$$

4.7 STILL WATER SYSTEM CALCULATIONS

Environmental professionals involved with still water system management are generally concerned with determining and measuring lake, pond, or reservoir morphometric data, which are commonly recorded on pre-impoundment topographic maps. Determining and maintaining water quality in still water systems is also a major area of concern for environmental engineers. Water quality involves the physical, chemical, and biological integrity of water resources. USEPA and other regulatory agencies promulgate water quality goals for the protection of water resources in watershed management. Again, most still water data are directly related to the morphological features of the water basin.

Mapping the water basin should be the centerpiece of any comprehensive study of a still water body. Calculations made from the map allow the investigator to accumulate and relate a lot of data concerning the still water body system. When determining and measuring the water quality of a still water body, several different models are used. The purpose of modeling is to help the environmental engineer organize an extended project. Modeling is a direct measurement method intended for a smaller body of water (e.g., lake, pond, reservoir); for example, water budget models and energy budget (lake evaporation) models can be used.

4.7.1 STILL WATER BODY MORPHOMETRY CALCULATIONS

The still water body volume, shoreline development index (SDI), and mean depth can be calculated using the formulas provided by Wetzel (1975) and Cole (1994).

4.7.1.1 Volume

The volume (V) of a still water body can be calculated when the area circumscribed by each isobath (i.e., each subsurface contour line) is known. The formula for water body volume is as follows (Wetzel, 1975):

$$V = \sum_{i=0}^n \frac{h}{3} \left(A_i + A_{i+1} + \sqrt{A_i \times A_{i+1}} \right) \quad (4.16)$$

where

V = Volume (ft³, ac-ft, m³).

h = Depth of the stratum (ft, m).

i = Number of depth stratum.

A_i = Area at depth i (ft², ac, m²).

The formula for the volume of water between the shoreline contour (z_0) and the first subsurface contour (z_1) is as follows (Cole, 1994):

$$V_{z_1-z_0} = \frac{1}{3} \left(A_{z_0} + A_{z_1} + \sqrt{(A_{z_0} + A_{z_1})(z_1 - z_0)} \right) \quad (4.17)$$

where

z_0 = Shoreline contour.

z_1 = First subsurface contour.

A_{z_0} = Total area of the water body.

A_{z_1} = Area limited by the z_1 line.

4.7.1.2 Shoreline Development Index

The shoreline development index (D_L) is a comparative figure relating the shoreline length to the circumference of a circle that has the same area as the still water body. The smallest possible index would be 1.0. For the following formula, both L and A must be in consistent units for this comparison—for example, meters and square meters.

$$D_L = \frac{L}{2\sqrt{\pi A}} \quad (4.18)$$

where

D_L = Shoreline development index.

L = Length of shoreline (miles, m).

A = Surface area of lake (ac, ft², m²).

4.7.1.3 Mean Depth

The still water body volume divided by its surface area will yield the mean depth. Remember to keep the units the same. If volume is in cubic meters, then area must be in square meters. The equation is as follows:

$$\bar{D} = \frac{V}{A} \quad (4.19)$$

where

$\bar{D}$ = Mean depth (ft, m).

V = Volume of lake (ft³, ac-ft, m³).

A = Surface area (ft², ac, m²).

■ EXAMPLE 4.32

Problem: A pond has a shoreline length of 8.6 miles. Its surface area is 510 acres. Its maximum depth is 8.0 feet. The areas for each foot depth are 460, 420, 332, 274, 201, 140, 110, 75, 30, and 1. Calculate the volume of the lake, shoreline development index, and mean depth of the pond.

Solution: Compute the volume of the pond:

$$\begin{aligned}
 V &= \sum_{i=0}^n \frac{h}{3} (A_i + A_{i+1} + \sqrt{A_i \times A_{i+1}}) \\
 &= \frac{1}{3} \left[\begin{aligned}
 &(510 + 460 + \sqrt{510 \times 460}) + (460 + 420 + \sqrt{460 \times 420}) \\
 &+ (420 + 332 + \sqrt{420 \times 332}) + (332 + 274 + \sqrt{332 \times 274}) \\
 &+ (274 + 201 + \sqrt{274 \times 201}) + (201 + 140 + \sqrt{201 \times 140}) \\
 &+ (140 + 110 + \sqrt{140 \times 110}) + (110 + 75 + \sqrt{110 \times 75}) \\
 &+ (75 + 30 + \sqrt{75 \times 30}) + (30 + 1 + \sqrt{30 \times 0})
 \end{aligned} \right] \\
 &= 1/3 \times 6823 = 2274 \text{ acre-ft}
 \end{aligned}$$

Compute the shoreline development index:

$$A = 510 \text{ acres} = 510 \text{ acres} \times \frac{1 \text{ m}^2}{640 \text{ acres}} = 0.7969 \text{ m}^2$$

$$D_L = \frac{L}{2\sqrt{\pi A}} = \frac{8.60}{2\sqrt{3.14 \times 0.7969}} = \frac{8.60}{3.16} = 2.72$$

Compute the mean depth:

$$\bar{D} = \frac{V}{A} = \frac{2274 \text{ acre-ft}}{510 \text{ acres}} = 4.46 \text{ ft}$$

4.7.1.4 Bottom Slope

$$S = \frac{\bar{D}}{D_m} \quad (4.20)$$

where

S = Bottom slope.

$\bar{D}$ = Mean depth (ft, m).

D_m = Maximum depth (ft, m).

4.7.1.5 Volume Development

Another morphometric parameter is volume development (D_v) (Cole, 1994). This metric compares the shape of the still water basin to an inverted cone with a height equal to D_m and a base equal to the still water body's surface area:

$$D_v = 3 \times \frac{\bar{D}}{D_m} \quad (4.21)$$

4.7.1.6 Water Retention Time

$$RT = \frac{\text{Storage capacity (acre-ft, m}^3\text{)}}{\text{Annual runoff (acre-ft/yr, m}^3\text{/yr)}} \quad (4.22)$$

where RT is retention time (years).

4.7.1.7 Ratio of Drainage Area to Still Water Body Capacity

$$R = \frac{\text{Drainage area (acre, m}^2\text{)}}{\text{Storage capacity (acre-ft, m}^3\text{)}} \quad (4.23)$$

■ EXAMPLE 4.33

Problem: Assume annual rainfall is 38.8 inches and watershed drainage is 10,220 acres. Using the data provided in Example 4.32, calculate the bottom slope, volume development, water retention time, and ratio of drainage area to lake capacity.

Solution: First determine the bottom slope:

$$S = \frac{\bar{D}}{D_m} = \frac{4.46}{8.0} = 0.56 \text{ ft}$$

Calculate volume development:

$$D_v = 3 \times \frac{\bar{D}}{D_m} = 3 \times 0.56 = 1.68 \text{ ft}$$

Calculate water retention time:

$$\text{Storage capacity} = 2274 \text{ acre-ft}$$

$$\begin{aligned} \text{Annual runoff} &= 38.8 \text{ in./yr} \times 10,220 \text{ acres} \\ &= 38.8 \text{ in./yr} \times 1 \text{ ft/12 in.} \times 10,220 \text{ acres} = 33,045 \text{ acre-ft/year} \end{aligned}$$

$$\text{Retention time} = \frac{\text{Storage capacity}}{\text{Annual runoff}} = \frac{2274}{33,045} = 0.069 \text{ years}$$

Now calculate the ratio (R) of drainage area to lake capacity:

$$R = \frac{\text{Drainage area}}{\text{Storage capacity}} = \frac{10,220}{2274} = \frac{4.49}{1}$$

4.7.2 STILL WATER SURFACE EVAPORATION

In lake, reservoir, and pond management, knowledge of evaporative processes is important to the environmental professional in understanding how water losses through evaporation are determined. Evaporation increases the storage requirement and decreases the yield of lakes and reservoirs. Several models and empirical methods are used for calculating lake and reservoir evaporative processes. The following sections discuss applications of the water budget and energy budget models, along with four empirical methods: Priestly–Taylor, Penman, DeBruin–Keijman, and Papadakis.

4.7.2.1 Water Budget Model

The water budget model for lake evaporation is used to estimate lake evaporation in some areas. It depends on accurate measurement of the inflow and outflow of the lake and is expressed as

$$\Delta S = P + R + G_I - G_O - E - T - O \quad (4.24)$$

where

ΔS = Change in lake storage (mm).

P = Precipitation (mm).

R = Surface runoff or inflow (mm).

G_I = Groundwater inflow (mm).

G_O = Groundwater outflow (mm).

E = Evaporation (mm).

T = Transpiration (mm).

O = Surface water release (mm).

If a lake has little vegetation and negligible groundwater inflow and outflow, lake evaporation (E) can be estimated by

$$E = P + R - O \pm \Delta S \quad (4.25)$$

4.7.2.2 Energy Budget Model*

The energy budget (Lee and Swancar, 1996) is recognized as the most accurate method for determining lake evaporation. It is also the most costly and time-consuming method (Mosner and Aulenbach, 2003). The evaporation rate is given by

$$E_{EB} = \frac{Q_s - Q_r + Q_a + Q_{ar} - Q_{bs} + Q_v - Q_x}{L(1 + BR) + T_0} \quad (4.26)$$

where

E_{EB} = Evaporation (cm/day).

Q_s = Incident shortwave radiation (cal/cm²/day).

Q_r = Reflected shortwave radiation (cal/cm²/day).

Q_a = Incident longwave radiation from atmosphere (cal/cm²/day).

Q_{ar} = Reflected longwave radiation (cal/cm²/day).

Q_{bs} = Longwave radiation emitted by lake (cal/cm²/day).

Q_v = Net energy advected by streamflow, groundwater, and precipitation (cal/cm²/day).

Q_x = Change in heat stored in water body (cal/cm²/day).

L = Latent heat of vaporization (cal/g).

BR = Bowen ratio (dimensionless).

T_0 = Water-surface temperature (°C).

4.7.2.3 Priestly–Taylor Equation

The Priestly–Taylor equation (Winter et al., 1995) is used to calculate potential evapotranspiration, which is a measure of the maximum possible water loss from an area under a specified set of weather conditions or evaporation as a function of latent heat of vaporization and heat flux in a water body. It is defined as

$$PET = \alpha \times \left(\frac{s}{s + \gamma} \right) \left[\frac{(Q_n - Q_x)}{L} \right] \quad (4.27)$$

where

PET = Potential evapotranspiration (cm/day).

α = 1.26, a Priestly–Taylor empirically derived constant (dimensionless).

s = Slope of the saturated vapor pressure gradient (dimensionless).

γ = Psychrometric constant (dimensionless).

Q_n = Net radiation (cal/cm²/day).

Q_x = Change in heat stored in water body (cal/cm²/day).

L = Latent heat of vaporization (cal/g).

Note that s and γ are parameters derived from the slope of the saturated vapor pressure–temperature curve at the mean air temperature.

* Much of the following information is adapted from Mosner, M.S. and Aulenbach, B.T., *Comparison of Methods Used to Estimate Lake Evaporation for a Water Budget of Lake Seminole, Southwestern Georgia and Northwestern Florida*, U.S. Geological Survey, Atlanta, GA, 2003.

4.7.2.4 Penman Equation

$$E_0 = \frac{(\Delta/\gamma)H_e + E_a}{(\Delta/\gamma) + 1} \quad (4.28)$$

where

E_0 = Evapotranspiration.

Δ = Slope of the saturation absolute humidity curve at the air temperature.

γ = Psychrometric constant.

H_e = Evaporation equivalent of the net radiation.

E_a = Aerodynamic expression for evaporation.

4.7.2.5 DeBruin–Keijman Equation

The DeBruin–Keijman equation (Winter et al., 1995) determines evaporation rates as a function of the moisture content of the air above the water body, the heat stored in the still water body, and the psychrometric constant, which is a function of atmospheric pressure and latent heat of vaporization.

$$PET = \left(\frac{SVP}{0.95SVP + 0.63\gamma} \right) \times (Q_n - Q_x) \quad (4.29)$$

where SVP is the saturated vapor pressure at mean air temperature (millibars/K). All other terms have been defined previously.

4.7.2.6 Papadakis Equation

The Papadakis equation (Winter et al., 1995) does not account for the heat flux that occurs in the still water body to determine evaporation. Instead, the equation depends on the difference in the saturated vapor pressure above the water body at maximum and minimum air temperatures, and evaporation is defined by

$$PET = 0.5625[e_0 \max - (e_0 \min - 2)] \quad (4.30)$$

where all terms have been defined previously.

4.8 WASTEWATER STABILIZATION POND DESIGN EXAMPLE PROBLEMS

■ EXAMPLE 4.34

Problem: Design an anaerobic pond based on volume and per capita (Oswald, 1996), where

Design flow rate = $947 \text{ m}^3/\text{d}$
 Influent ultimate $\text{BOD}_5 (C_o) = 400 \text{ mg/L}$
 Effluent ultimate $\text{BOD}_5 (C_e) = 50 \text{ g/L}$
 Sewered population = 6000 people
 Maximum bottom temperature in local waters = 20°C
 Temperature of pond water at bottom of pond = 10°C

Solution:

1. Calculate the BOD_5 loading:

$$\text{BOD}_5 \text{ loading} = \text{Influent BOD}_5 \times \text{Flow rate}/1000 = 378.8 \text{ kg/day}$$

2. Design the anaerobic pond (fermentation pits). Except for systems with flows less than $200 \text{ m}^3/\text{day}$, always use two ponds so that one will be available for removing sludge when the pond is filled. The surface area of anaerobic ponds should be limited to 1000 m^2 , and they should be made as deep as possible to avoid turnover with oxygen intrusion. Minimum pit depth should be 4 m (13.1 ft).

Number of anaerobic ponds in parallel = Minimum of two ponds = 2
 BOD_5 loading on a single pond = 189.4 kg/day

Size the pond on the basis of load per unit volume:

Load per unit volume (varies with water temperature) = $0.189 \text{ kg/m}^3/\text{day}$
 Volume in one pond = 1002.7 m^3
 Hydraulic retention time (HRT) = 2.12 days
 Pond depth = Minimum of 4 meters = 4 m
 Pond surface area (assuming vertical walls) = 250.7 m^2
 Maximum pond surface area = 1000 m^2
 Number of ponds = 0.25; round to next largest number of ponds = 1
 Overflow rate in ponds = Total surface area/total flow rate = 1.89 m/day

Overflow rates of less than 1.5 m/day should retain parasite eggs and other particles as small as $20 \mu\text{m}$, which includes all but the smallest parasite eggs (ova). The size of the pond should be increased to reduce the overflow rate to 1.5 m/day .

Check pond volume per capita:

Total volume in ponds = Total BOD_5 loading/loading rate = 2005 m^3
 Pond volume per capita = Total volume/population = $0.33 \text{ m}^3/\text{cap}$

Pond volume per capita should be greater than $0.0566 \text{ m}^3/\text{person}$ as used in conventional separate digesters. When pit volume/capita exceeds that amount, fermentation can go to completion with only grit and refractory organics left to accumulate.

■ EXAMPLE 4.35

Problem: Design an anaerobic pond based on volumetric loading or detention times (Crites et al., 2006), given

Temperature (°C)	Detention Time (days)	BOD ₅ Reduction (%)
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

Solution:

For climates with temperatures exceeding 22°C:

Volumetric loading (BOD₅/m³/day) = up to 300 g

HRT approximately = 5 days

Depth = 2.5 to 5 m

Cold climates have a 50% estimated reduction in BOD₅:

Volumetric loading (BOD₅/m³/day) = as low as 40 g

HRT = 50 days (approx.)

Design data:

- *Input*

Flow = 18,925 m³/day

Influent BOD₅ = 250 mg/L

Temperature = 10°C

Depth = 3 m

Length to width ratio = 1

Volumetric loading (BOD₅/m³/day) = 60 g

HRT = 5 days

Slope = 3

- *Output volumetric loading*

Volume = 78,854 m³

Length = 171 m

Width = 171 m

- *Output detention time*

Volume = 94,625 m³

Length = 187 m

Width = 187 m

Detention time = 5 days

■ EXAMPLE 4.36

Problem: Design a facultative pond utilizing frequently used formulations.

Solution 1. The Wehner–Wilhelm equation is used when designing for conditions between ideal plug flow and complete mix. Plug flow assumes that there is no mixing or diffusion as the wastewater moves through the pond. Alternatively, the complete mix flow model assumes that the wastewater is instantaneously fully mixed upon entering the pond.

$$\frac{C_e}{C_o} = \frac{4ae^{1/(2D)}}{(1+a)^2(e^{a/(2D)}) - (1-a)^2(e^{-a/(2D)})}$$

where

C_e = Effluent BOD concentration (mg/L).

C_o = Influent BOD concentration (mg/L).

$a = (1 + 4k_t D)^{0.5}$, where k is a first-order reaction rate constant (day^{-1}), t is the hydraulic retention time (days), and D is a dimensionless dispersion number $= H/vL = Ht/L^2$, where H is the axial dispersion coefficient (area per unit time), v is the fluid velocity (length per unit time), and L is the length of travel path of a typical particle.

e = Base of natural logarithms = 2.7183.

Dispersion numbers measured in wastewater ponds range from 0.1 to 2.0, with most values being less than 1.0. The selection of a value for D can dramatically affect the detention time required to produce a given quality effluent. The selection of a design value for k can have an equal effect. Typically, a modified form of the Thirumurthi (1974) chart is used to facilitate solving for D . Taken from such a chart we have

$$D = \frac{0.184 [tv(W + 2d)]^{0.489} (W)^{1.511}}{(Ld)^{1.489}}$$

where

D = Dimensionless dispersion number.

t = Hydraulic retention time (HRT) (days).

v = Kinematic viscosity (m^2/day).

W = Width of pond (m).

d = Liquid depth of pond (m).

L = Length of pond (m).

The variation of the reaction rate constant k with the water temperature is determined by

$$k_t = k_{20}(1.09)^{T-20}$$

where

k_t = Reaction rate at water temperature T /day.

k_{20} = Reaction rate at 20°C = 0.15/day.

T = Operating water temperature ($^\circ\text{C}$).

Use the following data to design a facultative pond system:

Q = Flow rate = 3785 m³/day (MGD)

C_o = Influent BOD₅ = 200 mg/L

C_e = Required effluent BOD₅ = 30 mg/L

Operating water temperature = 5°C

k_t = Reaction rate at 20°C = 0.15/day

Calculate k_t , the reaction rate at water temperature T /day:

$$k_t = k_{20}(1.09)^{T-20} = 0.04118$$

First iteration—solve for a first.

t_1 = Assumed HRT = 53.9 days

D = Assumed dimensionless dispersion number = 0.1

$$a = (1 + 4k_t D)^{0.5}$$

$$a_1 = 1.37399$$

Calculate the dimensions of the pond.

Length-to-width ratio = 3

ν = Kinematic viscosity = 0.1312 m²/day

t = Optimum HRT (final iteration) = 53.9 days

d = Liquid depth of pond = 2.45 m (8.0379 ft)

Volume = 204,012 m³ (53.9 MG)

Divide the flow into streams.

Number of streams = 1

Volume in one stream = 204,012 m³

Divide volume into three equal volumes.

Volume in one pond = 68,004 m³ (18.0 MG)

Surface area of each = 2.78 m² (6.9 ac)

Theoretical HRT in each pond = 53.9 days

Surface area = $L \times W$ = 288.6 m² (946.7 ft²) $\times$ 96.2 m² (315.6 ft²)

Approximately measured HRT is a value of 1/2 the theoretical value t_d = 26.95 days.

The following equation was developed by Polprasert and Bhattarai (1985) to improve D value accuracy for the Wehner–Wilhelm equation based on a measured HRT. With measured HRT (assumed to be 1/2) and dimensions of one cell, the accurate dispersion number is

$$t_d = 26.95 \text{ days}$$

$$D = \frac{\left[0.184(t \times v(W + 2d))^{0.489} \times W^{1.511} \right]}{(L \times D)^{1.489}} = 0.185$$

With the theoretical detention time, the dispersion number is

$$t_d = 53.9 \text{ days}$$

$$D = 0.2597$$

Determine the dimensions of each cell using the theoretical HRT and initial dispersion number:

$$\text{Length-to-width ratio} = 3$$

$$L = 288.57 \text{ m (946.7 ft)}$$

$$W = 96.19 \text{ (315.6 ft)}$$

Calculate the effluent BOD_5 concentration using the theoretical HRT, as the Wehner–Wilhelm equation was developed based on the theoretical value. Total HRT is used because the equation represents the entire system.

$$D = 0.2597$$

$$a_3 = 1.374$$

$$C_e = [4a \times e^{1/(2D)}] / [(1 + a)^2(e^{a/(2D)}) - (1 - a)^2(e^{-a/(2D)})] / C_o = 30 \text{ mg/L}$$

Solution 2. According to the organic loading method:

$$\text{Depth} = 2.45 \text{ m (8.04 ft)}$$

$$\text{Organic load} = \text{BOD}_5 \times Q/1000 = 757 \text{ kg/day (1669 lb/day)}$$

$$\text{Organic loading rate, kg/ha/day (lb/ac/day)} = 27 \text{ (60); } 18 \text{ (40); } 14 \text{ (30); } 5 \text{ (10)}$$

$$\text{Area required, ha (ac)} = 11 \text{ (28); } 17 \text{ (42); } 23 \text{ (56); } 68 \text{ (167)}$$

$$\text{Volume (m}^3\text{)} = 275,774; 413,660; 551,547; 1,654,641$$

Area or volume is divided into three or four cells in series.

Solution 3. According to the complete mix model:

$$\frac{C_n}{C_o} = \left(\frac{1}{1 + k_c t_n} \right)^n \quad t = \left(\frac{n}{k} \right) \left[\left(\frac{C_o}{C_n} \right)^{1/n} - 1 \right]$$

Q = Flow rate = 3784 m³/day (1.00 MGD)

Influent BOD₅ = 200 mg/L

Effluent BOD₅ = 30 mg/L

Influent suspended solids = 150mg/L

Number of cells in series = 3

Water temperature = 5°C

Reaction rate at 35°C = 0.5/day

Temperature correction coefficient = 1.085

k_t = 0.043/day

Hydraulic retention time (HRT) = 61.17 days

Volume = 231,533 m³ (61.16 MG)

Depth = 2.25 m (8 ft)

Surface area = 9.45 ha (23.4 ac)

Solution 4. According to the Gloyna method:

$$V = 0.035Q(\text{BOD}_5)(1.099)^{LIGHT(35-T/250)}$$

where

Q = Flow rate = 3785 m³/day (0.999360 MGD)

BOD₅ = 200 mg/L

$LIGHT$ = 200 Langley's

Temperature correction coefficient = 1.099

Temperature = 5°C

Volume = 255,334 m³ (67.45 MG)

Predicted effluent BOD₅ = 80 to 90% reduction = 20 to 40 mg/L

Total volume will be divided into three or four equal cells.

Solution 5. According to the plug flow method:

$$\frac{C_e}{C_o} = \exp[-k_p t] \quad t = \ln\left(\frac{C_e}{C_o}\right)\left(\frac{1}{k_p}\right)$$

where

C_e = Effluent BOD₅ = 30 mg/L

C_o = Influent BOD₅ = 200 mg/L

k_p = Plug flow first-order reaction rate at 20°C = 0.07/day

t = Hydraulic retention time (HRT) = 98.7 days

TC = Temperature correction coefficient = 1.09

T = Water temperature = 50°C

k_{pT} = Plug flow reaction rate at T (°C) = 0.01922/day

With influent and effluent specified, calculate HRT (t):

$$t = 98.7 \text{ days}$$

With influent and hydraulic detention time specified, calculate effluent.

$$C_e = 30 \text{ mg/L}$$

$$\text{Volume} = Q \times t = 373,646 \text{ m}^3 \text{ (98 MG)}$$

$$\text{Surface area} = V/\text{Depth} = 152,508 \text{ m}^2 \text{ (37.7 ac)}$$

Summary of Results

Method	HRT (days)	Volume (m ³)	Surface Area (m ²)
Wehner–Wilhelm	53.9	204,012	83,270
Surface area	145.7	551,547	225,124
Complete mix	61.2	231,533	94,503
Gloyna	67.5	255,334	104,218
Plug flow	98.7	373,646	152,508

Note: Values for surface area are based on a surface loading rate of 34 kg/ha/day (30 lb/ac/day). At 66 kg/ha/day (60 lb/ac/day), the results would be close to the others but a reliable effluent BOD₅ of 30 mg/L might not be as attainable.

■ EXAMPLE 4.37

Problem: Compare the detention times for the same BOD₅ removal levels in partial mix aerated ponds having one to five cells. Assume the following:

$$C_o = 200 \text{ mg/L}$$

$$k = 0.28/\text{day}$$

$$T_w = 20^\circ\text{C}$$

Solution: First solve the equation for a single-cell system.

$$t = \left(\frac{n}{k}\right) \left[\left(\frac{C_o}{C_n} \right)^{1/n} - 1 \right] = \left(\frac{1}{0.28} \right) \left[\left(\frac{200}{30} \right)^{1/1} - 1 \right] = 20.2 \text{ days}$$

Similarly,

$$\text{For } n = 2, t = 11 \text{ days}$$

$$\text{For } n = 3, t = 9.4 \text{ days}$$

$$\text{For } n = 4, t = 8.7 \text{ days}$$

$$\text{For } n = 5, t = 8.2 \text{ days}$$

Continuing to increase n will result in the HRT being equal to the HRT in a plug flow reactor. It can be seen from the tabulation above that the advantages diminish after the third or fourth cell.

■ EXAMPLE 4.38

Problem: Design a four-cell partial mix aerated pond with two trains to remove BOD₅ for the following environmental conditions and wastewater characteristics:

$Q = 1136 \text{ m}^3/\text{d}$ (0.3 MGD)
 $C_o = 220 \text{ mg/L}$
 C_e from fourth cell = 30 mg/L
 $k_{20} = 0.276 \text{ day}$
 Air temperature (winter) = 8°C
 Air temperature (summer) = 25°C
 Elevation = 50 m (164 ft)
 Depth = 4 m (13.1 ft)

Solution:

Given:

Flow rate = $Q = 568 \text{ m}^3/\text{day}$
 Influent BOD₅ = 220 mg/L
 Influent TSS = 200 mg/L
 Total N = 30 mg/L
 Total P = 10 mg/L
 Reaction rate at 20°C = 0.276/day
 Influent temperature = 15°C
 Winter air temperature = $T_a = 8^\circ\text{C}$
 Summer air temperature = $T_a = 25^\circ\text{C}$
 Temperature correction coefficient = 1.09
 Surface elevation = 50 m
 Minimum DO = 2 mg/L
 Depth = 4 m
 Length-to-width ratio = 2
 Side slope = 3

1. For Cell 1,

Assume winter pond temperature = 12.06°C.

Determine the volume of Cell 1 in the pond system.

Correct reaction rate for temperature = $k_t = k_{20}(1.036)^{(T-20)} = 0.210/\text{day}$
 Cell 1 HRT = 3.60 days
 Cell 1 effluent BOD₅ = $C_o/(1 + k_d) = 125.69 \text{ mg/L}$
 Cell 1 volume = 2044.80 m³

Calculate the dimensions of Cell 1 at the water surface and the surface area.

Depth = 4 m
 Width = 24.51 m
 Length = 49.02 m
 Cell 1 surface area = 1201.61 m² (0.134 ac)

Check the pond temperature using the cell area calculated above and the equation shown below:

$$\text{Cell 1 } T_w = (AfT_a + QT_i)/(Af + Q) = 11.4^\circ\text{C}$$

If calculated T_w differs from the assumed water temperature, iteration is necessary.

Add a freeboard = 0.90 m

Dimensions at top of dike in Cell 1:

Width of top of dike = 29.91 m

Length of top of dike = 54.42 m

2. For Cell 2,

Influent temperature = 11.4°C

Determine the volume of Cell 2 in the pond system.

Correct reaction rate for temperature = $k_t = k_{20}(1.009)^{(T-20)} = 0.20/\text{day}$

Cell 2 HRT = 3.50 days

Cell 2 influent $\text{BOD}_5 = 125.69 \text{ mg/L}$

Cell 2 effluent $\text{BOD}_5 = 73.39 \text{ mg/L}$

Cell 2 volume = 1988.00 m^3

Calculate the dimensions of Cell 2 at the water surface and the surface area.

Depth = 4.00 m

Width = 24.28 m

Length = 48.56 m

Cell 2 surface area = 1179.11 m^2 (0.134 ac)

Check the pond temperature using the cell area calculated above and the equation shown below:

$$\text{Cell 2 } T_w = (AfT_a + QT_i)/(Af + Q) = 9.67^\circ\text{C}$$

Add a freeboard = 0.90 m

Dimensions at top of dike in Cell 2:

Width of top of dike = 29.68 m

Length of top of dike = 53.96 m

3. For Cell 3,

Influent temperature = 9.7°C

Determine the volume of Cell 3 in the pond system.

Correct reaction rate for temperature = $k_t = 0.19/\text{day}$

Cell 3 HRT = 3 days

Cell 3 influent $\text{BOD}_5 = 73.39 \text{ mg/L}$

Cell 3 effluent $BOD_5 = 46.61 \text{ mg/L}$

Cell 3 volume = 1704.00 m^3

Calculate the dimensions of Cell 3 at the water surface and the surface area.

Depth = 4.00 m

Width = 23.07 m

Length = 46.14 m

Cell 3 surface area = 1064.56 m^2 (0.134 ac)

Check the pond temperature using the cell area calculated above and the equation shown below:

$$\text{Cell 3 } T_w = (AfT_a + QT_i)/(Af + Q) = 8.86^\circ\text{C}$$

Add a freeboard = 0.90 m

Dimensions at top of dike in Cell 3:

Width of top of dike = 28.47 m

Length of top of dike = 51.54 m

4. For Cell 4,

Influent temperature = 8.86°C

Determine the volume of Cell 4 in the pond system.

Correct reaction rate for temperature = $k_t = 0.19/\text{day}$

Cell 4 HRT = 3 days

Cell 4 influent $BOD_5 = 46.61 \text{ mg/L}$

Cell 4 effluent $BOD_5 = 29.91 \text{ mg/L}$

Cell 4 volume = 1704.00 m^3

Calculate the dimensions of Cell 4 at the water surface and the surface area.

Depth = 4.00 m

Width = 23.07 m

Length = 46.14 m

Cell 4 surface area = 1064.56 m^2 (0.134 ac)

Check the pond temperature using the cell area calculated above and the equation shown below:

$$\text{Cell 4 } T_w = (AfT_a + QT_i)/(Af + Q) = 8.44^\circ\text{C}$$

Add freeboard = 0.90 m

Dimensions at top of dike in Cell 4:

Width of top of dike = 28.47 m

Length of top of dike = 51.54 m

5. Determine the oxygen requirements for the pond system based on organic loading and water temperature. Maximum oxygen requirements will occur during the summer months.

$$T_w = (AfT_a + QT_i)/(Af + Q)$$

$$\text{Cell 1 } T_w = 20.1^\circ\text{C}$$

$$\text{Cell 2 } T_w = 22.6^\circ\text{C}$$

$$\text{Cell 3 } T_w = 23.8^\circ\text{C}$$

$$\text{Cell 4 } T_w = 24.4^\circ\text{C}$$

Calculate the organic load (OL) in the influent wastewater.

Cell 1:

$$\text{OL}_1 = C_0 \times Q = 5.12 \text{ kg/hr}$$

Calculate the effluent BOD₅ from Cell 1 using the equations below at T_w for summer.

$$k_{T_w} = k_{20} \times (\text{Temperature coefficient})^{(T_w - 20)} = 0.28/\text{day}$$

$$C_1 = C_0 / [(k_t) + 1] = 110.08 \text{ mg/L}$$

$$\text{Winter} = 125.69 \text{ mg/L}$$

Cell 2:

$$\text{OL}_2 = C_1 \times Q = 2.61 \text{ kg/hr}$$

$$k_{T_w} = k_{20} \times (\text{Temperature coefficient})^{(T_w - 20)} = 0.30/\text{day}$$

$$C_2 = C_1 / [(k_t) + 1] = 53.45 \text{ mg/L}$$

$$\text{Winter} = 73.39 \text{ mg/L}$$

Cell 3:

$$\text{OL}_3 = C_2 \times Q = 1.26 \text{ kg/hr}$$

$$k_{T_w} = k_{20} \times (\text{Temperature coefficient})^{(T_w - 20)} = 0.32/\text{day}$$

$$C_3 = C_2 / [(k_t) + 1] = 27.46 \text{ mg/L}$$

$$\text{Winter} = 46.61 \text{ mg/L}$$

Cell 4:

$$\text{OL}_4 = C_3 \times Q = 0.65 \text{ kg/hr}$$

$$k_{T_w} = k_{20} \times (\text{Temperature coefficient})^{(T_w - 20)} = 0.32/\text{day}$$

$$C_4 = C_3 / [(k_t) + 1] = 13.97 \text{ mg/L}$$

$$\text{Winter} = 29.91 \text{ mg/L}$$

DO is assumed to be a multiple of organic loading. Multiplication factor (MF) = 1.50.

$$\text{Cell 1 DO} = \text{OL}_1 \times \text{MF} = 7.81 \text{ kg/hr}$$

$$\text{Cell 2 DO} = \text{OL}_2 \times \text{MF} = 3.91 \text{ kg/hr}$$

$$\text{Cell 3 DO} = \text{OL}_3 \times \text{MF} = 1.90 \text{ kg/hr}$$

$$\text{Cell 4 DO} = \text{OL}_4 \times \text{MF} = 0.97 \text{ kg/hr}$$

6. Use the following equation to calculate the equivalent O_2 transfer:

$$N = N_{OD}/a[(C_{sw} - C_L)/C_s](\text{Temperature factor})^{(T_w - 20)}$$

where

N_{OD} = DO in various cells

$$C_{sw} = b \times C_{ss} \times P$$

$$b = 0.90$$

P = Ratio of barometric pressure at pond site to pressure at sea level = 0.80

Cell 1 tapwater O_2 saturation value $C_{ss} = 9.15 \text{ mg/L}$

Cell 2 tapwater O_2 saturation value $C_{ss} = 8.74 \text{ mg/L}$

Cell 3 tapwater O_2 saturation value $C_{ss} = 8.56 \text{ mg/L}$

Cell 4 tapwater O_2 saturation value $C_{ss} = 8.46 \text{ mg/L}$

Cell 1 $C_{sw} = 6.59 \text{ mg/L}$

Cell 2 $C_{sw} = 6.29 \text{ mg/L}$

Cell 3 $C_{sw} = 6.16 \text{ mg/L}$

Cell 4 $C_{sw} = 6.09 \text{ mg/L}$

a = O_2 transfer in wastewater/ O_2 transfer in tapwater = 0.90

C_L = Minimum O_2 concentration to be maintained in wastewater = 2.00 mg/L

C_s = O_2 saturation value of tapwater at 20°C and 1 atm = 9.17 mg/L

Temperature factor = 1.025

$N_1 = 17.29 \text{ kg/hr}$

$N_2 = 8.70 \text{ kg/hr}$

$N_3 = 4.23 \text{ kg/hr}$

$N_4 = 2.18 \text{ kg/hr}$

7. Evaluate surface and diffused air aeration equipment to satisfy O_2 requirement only.

Power required for surface aerators = 1.90 kg O_2 /kWh (1.40 kg O_2 /hp-hr)

Power required for diffused air = 2.70 kg O_2 /kWh (2.00 kg O_2 /hp-hr)

Total power for surface aeration:

$$\text{Cell 1} = 9.10 \text{ kW} = 12.35 \text{ hp}$$

$$\text{Cell 2} = 4.58 \text{ kW} = 6.21 \text{ hp}$$

$$\text{Cell 3} = 2.23 \text{ kW} = 2.99 \text{ hp}$$

$$\text{Cell 4} = 1.15 \text{ kW} = 1.54 \text{ hp}$$

Total power for diffused aeration:

$$\text{Cell 1} = 6.40 \text{ kW} = 8.64 \text{ hp}$$

$$\text{Cell 2} = 3.22 \text{ kW} = 4.35 \text{ hp}$$

$$\text{Cell 3} = 1.57 \text{ kW} = 2.12 \text{ hp}$$

$$\text{Cell 4} = 0.81 \text{ kW} = 1.09 \text{ hp}$$

These surface and diffused aerator power requirements must be corrected for gearing and blower efficiency:

$$\text{Gearing efficiency} = 0.90$$

$$\text{Blower efficiency} = 0.90$$

Total power required corrected for efficiency:

$$\text{Cell 1} = 10.11 \text{ kW} = 13.48 \text{ hp}$$

$$\text{Cell 2} = 5.09 \text{ kW} = 4.31 \text{ hp}$$

$$\text{Cell 3} = 2.48 \text{ kW} = 1.20 \text{ hp}$$

$$\text{Cell 4} = 1.27 \text{ kW} = 0.31 \text{ hp}$$

$$\text{Total power (surface aerators)} = 18.95 \text{ kW} = 19.30 \text{ hp}$$

$$\text{Power cost/kWh} = \$0.06$$

$$\text{Total power costs for surface aerators} = \$9958.02/\text{yr}$$

$$\text{Cell 1} = 7.11 \text{ kW} = 9.49 \text{ hp}$$

$$\text{Cell 2} = 3.58 \text{ kW} = 3.03 \text{ hp}$$

$$\text{Cell 3} = 1.74 \text{ kW} = 0.85 \text{ hp}$$

$$\text{Cell 4} = 0.90 \text{ kW} = 0.22 \text{ hp}$$

$$\text{Total power (diffused aerators)} = 13.13 \text{ kW} = 13.58 \text{ hp}$$

$$\text{Power cost/kWh} = \$0.06$$

$$\text{Total power costs for diffused aeration} = \$7007.49/\text{yr}$$

These power requirements are approximate values and should be used for the preliminary selection of equipment.

■ EXAMPLE 4.39

Problem: Compare detention times for the same BOD_5 removal levels in complete mix aerated ponds having one to five cells. Assume the following:

$$C_o = 200 \text{ mg/L}$$

$$k = 2.5/\text{day}$$

$$T_w = 20^\circ\text{C}$$

Solution: Solve the following equation for a single-cell system:

$$t = \left(\frac{n}{k}\right) \left[\left(\frac{C_o}{C_n}\right)^{1/n} - 1 \right] = \left(\frac{1}{2.5}\right) \left[\left(\frac{200}{30}\right)^{1/1} - 1 \right] = 2.7 \text{ days}$$

Similarly,

For $n = 2$, $t = 1.04$ days

For $n = 3$, $t = 0.35$ day

For $n = 4$, $t = 0.24$ day

Continuing to increase n will result in the detention time being equal to the detention time in a plug flow reactor. It can be seen from the tabulation above that the advantages diminish after the third cell. This advantage is lost because of the need for a hydraulic retention time of approximately 1-1/2 days for the biomass to develop.

■ EXAMPLE 4.40

Problem: Design a four-cell complete mix aerated pond with two trains to remove BOD₅ for the following environmental conditions and wastewater characteristics:

$Q = 1136 \text{ m}^3/\text{day}$ (0.3 MGD)

$C_o = 220 \text{ mg/L}$

C_e from fourth cell = 10 mg/L

$k_{20} = 2.5/\text{day}$

Air temperature (winter) = 8°C

Air temperature (summer) = 25°C

Elevation = 50 m

DO = 2 mg/L in all cells

Depth = 4 m (13.1 ft).

Solution:

Given:

Flow rate = $Q = 568 \text{ m}^3/\text{day}$

Influent BOD₅ = 220 mg/L

Influent TSS = 200 mg/L

Total N = 30 mg/L

Total P = 10 mg/L

Reaction rate at 20°C = 2.5/day

Influent temperature = 15°C

Winter air temperature = $T_a = 8^\circ\text{C}$

Summer air temperature = $T_a = 25^\circ\text{C}$

Units conversion factor = $f = 0.50$

Temperature correction coefficient = 1.09

Surface elevation = 50 m

Minimum DO concentration = 2 mg/L

Depth = 4 m
 Length-to-width ratio = 2
 Side slope = 3

1. For Cell 1,

Assume winter pond temperature = 12.74°C

Determine the volume of Cell 1 in the pond system.

Correct reaction rate for temperature $k_t = k_{20}(1.09)^{(T-20)} = 1.34/\text{day}$

Cell 1 HRT = 1 day

Cell 1 effluent $\text{BOD}_5 = 94.13 \text{ mg/L}$

Cell 1 volume = 568 m³

Calculate the dimensions of Cell 1 at the water surface and the surface area.

Depth = 4 m
 Width = 16.48 m
 Length = 32.97 m
 Cell 1 surface area = 543.40 m² (0.134 ac)

Check the pond temperature using the cell area calculated above and the equation shown below:

$$\text{Cell 1 } T_w = (AfT_a + QT_i)/(Af + Q) = 12.74^\circ\text{C}$$

If calculated T_w differs from assumed water temperature, iteration is necessary.

Add a freeboard = 0.90 m

Dimensions at top of dike in Cell 1:

Width of top of dike = 21.88 m
 Length of top of dike = 38.37 m

2. For Cell 2,

Influent water temperature = 12.74°C

Determine the volume of Cell 2 in the pond system.

Correct reaction rate for temperature $k_t = k_{20}(1.09)^{(T-20)} = 1.34/\text{day}$

Cell 2 HRT = 1 day

Cell 2 effluent $\text{BOD}_5 = 40.28 \text{ mg/L}$

Cell 2 influent $\text{BOD}_5 = 94.13 \text{ mg/L}$

Cell 2 volume = 568 m³

Calculate the dimensions of Cell 2 at the water surface and the surface area:

Depth = 4 m
 Width = 16.48 m
 Length = 32.97 m
 Cell 2 surface area = 543.40 m² (0.134 ac)

Check the pond temperature using the cell area calculated above and the equation shown below:

$$\text{Cell 2 } T_w = (AfT_a + QT_i)/(Af + Q) = 11.20^\circ\text{C}$$

Add a freeboard = 0.90 m

Dimensions at top of dike in Cell 2:

Width of top of dike = 21.88 m

Length of top of dike = 38.37

3. For Cell 3

Influent temperature = 11.20°C

Determine the volume of Cell 3 in the pond system.

Correct reaction rate for temperature $k_t = 1.17/\text{day}$

Cell 3 HRT = 1 day

Cell 3 effluent $\text{BOD}_5 = 18.55 \text{ mg/L}$

Cell 3 influent $\text{BOD}_5 = 40.28 \text{ mg/L}$

Cell 3 volume = 568 m^3

Calculate the dimensions of Cell 3 at the water surface and the surface area:

Depth = 4 m

Width = 16.48 m

Length = 32.97 m

Cell 3 surface area = 543.40 m^2 (0.134 ac)

Check the pond temperature using the cell area calculated above and the equation shown below:

$$\text{Cell 3 } T_w = (AfT_a + QT_i)/(Af + Q) = 10.17^\circ\text{C}$$

Add a freeboard = 0.90 m

Dimensions at top of dike in Cell 3:

Width of top of dike = 21.88 m

Length of top of dike = 38.37 m

4. For Cell 4,

Influent temperature = 10.17°C

Determine the volume of Cell 4 in the pond system.

Correct reaction rate for temperature $k_t = 1.07/\text{day}$

Cell 4 HRT in = 1 day

Cell 4 effluent $\text{BOD}_5 = 8.96 \text{ mg/L}$

Cell 4 influent $\text{BOD}_5 = 18.55 \text{ mg/L}$

Cell 4 volume = 568 m^3

Calculate the dimensions of Cell 4 at the water surface and the surface area:

Depth = 4.00 m

Width = 16.48 m

Length = 32.97 m

Cell 4 surface area = 543.40 m² (0.134 ac)

Check the pond temperature using the cell area calculated above and the equation shown below:

$$\text{Cell 4 } T_w = (AfT_a + QT_i)/(Af + Q) = 9.47^\circ\text{C}$$

Add a freeboard = 0.90 m

Dimensions at top of dike in Cell 4:

Width of top of dike = 21.88 m

Length of top of dike = 38.37 m

5. Determine the oxygen requirements for the pond system based on organic loading and water temperature. Maximum oxygen requirements will occur during the summer months.

$$T_w = (AfT_a + QT_i)/(Af + Q)$$

$$\text{Cell 1 } T_w = 18.2^\circ\text{C}$$

$$\text{Cell 2 } T_w = 20.4^\circ\text{C}$$

$$\text{Cell 3 } T_w = 21.9^\circ\text{C}$$

$$\text{Cell 4 } T_w = 22.9^\circ\text{C}$$

Calculate the organic load (OL) in the influent wastewater.

Cell 1:

$$\text{OL}_1 = C_0 \times Q = 5.21 \text{ kg/hr}$$

Calculate the effluent BOD₅ from Cell 1 using the equations below at T_w for summer.

$$k_{T_w} = k_{20} \times (\text{Temperature coefficient})^{(T_w - 20)} = 2.15/\text{day}$$

$$C_1 = C_0 / [(k_d) + 1] = 69.90 \text{ mg/L}$$

$$\text{Winter} = 94.13 \text{ mg/L}$$

Cell 2:

$$\text{OL}_2 = C_1 \times Q = 1.65 \text{ kg/hr}$$

$$k_{T_w} = k_{20} \times (\text{Temperature coefficient})^{(T_w - 20)} = 2.59/\text{day}$$

$$C_2 = C_1 / [(k_d) + 1] = 19.45 \text{ mg/L}$$

$$\text{Winter} = 40.28 \text{ mg/L}$$

Cell 3:

$$OL_3 = C_2 \times Q = 0.46 \text{ kg/hr}$$

$$k_{Tw} = k_{20} \times (\text{Temperature coefficient})^{(Tw-20)} = 2.95/\text{day}$$

$$C_3 = C_2 / [(k_t) + 1] = 4.93 \text{ mg/L}$$

$$\text{Winter} = 18.55 \text{ mg/L}$$

Cell 4:

$$OL_4 = C_3 \times Q = 0.12 \text{ kg/hr}$$

$$k_{Tw} = k_{20} \times (\text{temperature coefficient})^{(Tw-20)} = 3.21/\text{day}$$

$$C_4 = C_3 / [(k_t) + 1] = 1.17 \text{ mg/L}$$

$$\text{Winter} = 8.96 \text{ mg/L}$$

DO is assumed to be a multiple of organic loading. Multiplication factor (MF) = 1.50.

$$\text{Cell 1 DO} = OL_1 \times MF = 7.81 \text{ kg/hr}$$

$$\text{Cell 2 DO} = OL_2 \times MF = 2.48 \text{ kg/hr}$$

$$\text{Cell 3 DO} = OL_3 \times MF = 0.69 \text{ kg/hr}$$

$$\text{Cell 4 DO} = OL_4 \times MF = 0.18 \text{ kg/hr}$$

6. Use the following equation to calculate the equivalent O_2 transfer:

$$N = N_{OD} / a [(C_{sw} - C_L) / C_s] (\text{Temperature factor})^{(Tw-20)}$$

where

$$N_{OD} = \text{DO in various cells}$$

$$C_{sw} = b \times C_{ss} \times P$$

$$b = 0.90$$

$$P = \text{Ratio of barometric pressure at pond site to pressure at sea level} = 0.80$$

$$\text{Cell 1 tapwater } O_2 \text{ saturation value } C_{ss} = 9.49 \text{ mg/L}$$

$$\text{Cell 2 tapwater } O_2 \text{ saturation value } C_{ss} = 9.10 \text{ mg/L}$$

$$\text{Cell 3 tapwater } O_2 \text{ saturation value } C_{ss} = 8.85 \text{ mg/L}$$

$$\text{Cell 4 tapwater } O_2 \text{ saturation value } C_{ss} = 8.69 \text{ mg/L}$$

$$\text{Cell 1 } C_{sw} = 6.84 \text{ mg/L}$$

$$\text{Cell 2 } C_{sw} = 6.55 \text{ mg/L}$$

$$\text{Cell 3 } C_{sw} = 6.37 \text{ mg/L}$$

$$\text{Cell 4 } C_{sw} = 6.26 \text{ mg/L}$$

$a = \text{O}_2 \text{ transfer in wastewater} / \text{O}_2 \text{ transfer in tapwater} = 0.90$

$C_L = \text{Minimum O}_2 \text{ concentration to be maintained in wastewater} = 2.00 \text{ mg/L}$

$C_s = \text{O}_2 \text{ saturation value of tapwater at } 20^\circ\text{C and } 1 \text{ atm} = 9.17 \text{ mg/L}$

Temperature factor = 1.025

$N_1 = 17.19 \text{ kg/hr}$

$N_2 = 5.50 \text{ kg/hr}$

$N_3 = 1.54 \text{ kg/hr}$

$N_4 = 0.39 \text{ kg/hr}$

7. Evaluate surface and diffused air aeration equipment to satisfy the O_2 requirement only.

Power required for surface aerators = $1.90 \text{ kg O}_2/\text{kWh}$ ($1.40 \text{ kg O}_2/\text{hp-hr}$)

Power required for diffused air = $2.70 \text{ kg O}_2/\text{kWh}$ ($2.00 \text{ kg O}_2/\text{hp-hr}$)

Total power for surface aeration:

Cell 1 = $9.05 \text{ kW} = 12.28 \text{ hp}$

Cell 2 = $2.89 \text{ kW} = 3.93 \text{ hp}$

Cell 3 = $0.81 \text{ kW} = 1.10 \text{ hp}$

Cell 4 = $0.21 \text{ kW} = 0.28 \text{ hp}$

Total power for diffused aeration:

Cell 1 = $6.37 \text{ kW} = 8.60 \text{ hp}$

Cell 2 = $2.04 \text{ kW} = 2.75 \text{ hp}$

Cell 3 = $0.57 \text{ kW} = 0.77 \text{ hp}$

Cell 4 = $0.14 \text{ kW} = 0.19 \text{ hp}$

These surface and diffused aerator power requirements must be corrected for gearing and blower efficiency:

Gearing efficiency = 0.90

Blower efficiency = 0.90

Total power required corrected for efficiency:

Cell 1 = $10.05 \text{ kW} = 13.48 \text{ hp}$

Cell 2 = $3.21 \text{ kW} = 4.31 \text{ hp}$

Cell 3 = $0.90 \text{ kW} = 1.20 \text{ hp}$

Cell 4 = $0.23 \text{ kW} = 0.31 \text{ hp}$

Total power (surface aerators) = $14.39 \text{ kW} = 19.30 \text{ hp}$

Power cost/kWh = \$0.06

Total power costs for surface aerators = \$7564.74/yr

Cell 1 = 7.07 kW = 9.49 hp

Cell 2 = 2.26 kW = 3.03 hp

Cell 3 = 0.63 kW = 0.85 hp

Cell 4 = 0.16 kW = 0.22 hp

Total power (diffused aerators) = 10.13 kW = 13.58 hp

Power cost/kWh = \$0.06

Total power costs for diffused aeration = \$5323.33/yr

These power requirements are approximate values and should be used for the preliminary selection of equipment.

8. Evaluate the power requirements for maintaining a complete mix reactor.

Power required to maintain solids suspension = 6.00 kW/1000 m³
(30.48 hp/MG)

Total power required in all cells = 3.41 kW = 4.57 hp

9. Total power required in system will be the sum of the maximum power required in each cell as measured above.

Assuming that complete mixing is to occur in all cells, use the first set shown below. An alternative is to use the power calculated for each cell to satisfy O₂ demand or a mixture of complete mix and O₂ requirements.

Power required for complete mix in all cells:

All cells = 3.41 kW

Total = 13.63 kW

Power costs = \$7164.98/year

Power requirements for each cell based on BOD₅ removal:

Cell 1 = 10.05 kW = 13.48 hp

Cell 2 = 3.21 kW = 4.31 hp

Cell 3 = 0.90 kW = 1.20 hp

Cell 4 = 0.23 kW = 0.31 hp

Total = 14.39 kW = 19.30 hp

Power costs = \$7564.74/year

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5 Design of Wastewater Stabilization Ponds

5.1 INTRODUCTION

To this point in the text the material presented has provided the reader with a fundamental preamble to the material to follow. We noted that wastewater treatment ponds have existed and have provided adequate treatment since 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 have been developed, published, and used by practitioners. Building on the material presented to this point, including the design equations and examples presented in the last chapter, the basic designs of the various pond types are presented in this chapter.

5.2 ANAEROBIC PONDS

Note: Based on our experience in providing training for college students and plant operator trainees via the regular college classroom and satellite short-course training centers for operator licensure preparation, we have found that when we associate a particular treatment process with something else or some other natural process we not only add color to our presentation but also a way to compare and retain the pertinent information. Consider, for example, the anaerobic bacteria that occur in the intestinal tract of ruminants (e.g., cattle, sheep, deer, camels, antelope) and do not need free oxygen to survive. Conditions in an anaerobic pond are similar in that they allow such bacteria to continue decomposing the remaining organic compounds in the manure (fats, proteins, and polysaccharides), producing methane and carbon dioxide. Anaerobic bacteria can be found throughout most of the pond's water column, but activity is concentrated immediately above the sludge layer (blanket). Again, by making this basic comparison between the digestive system of ruminants and the operation of anaerobic ponds, students and readers seem to better retain pond information and are able to differentiate between anaerobic ponds and the other types of ponds.

An anaerobic pond is a non-aerated, non-heated, and non-mixed deep impoundment, essentially free of dissolved oxygen (DO). The biochemical processes take place in deep basins, and such ponds are often used as preliminary treatment systems. Because they are typically more than 8 feet deep, the effects of oxygen (O_2) diffusion from the surface of an anaerobic pond 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. Biochemical oxygen demand (BOD_5) removals may reach 60%. 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. (Rule of thumb: Odor is not a problem until the neighbors complain; therefore, anaerobic ponds are not typically installed in neighborhood locations.) 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. Again, anaerobic ponds are deep and generally have a relatively longer hydraulic retention time (HRT), which allows solids to settle, sludge to be digested, and BOD_5 concentrations to be reduced.

In operation, raw wastewater is usually screened (via a bar screen) and then flows into a Parshall flume with a flow recorder to determine the inflow before it 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.

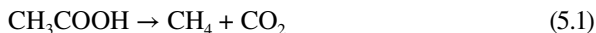
5.2.1 MICROBIOLOGY

In anaerobic ponds, stable products, such as carbon dioxide (CO_2) and methane (CH_4), are converted (degraded) from organic materials by anaerobic microorganisms. 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 they 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:



2. The reduction of carbon dioxide by hydrogen gas to form methane:



5.2.2 EQUILIBRIUM

When the two phases of degradation occur simultaneously in dynamic equilibrium, the system is working properly. 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 pH 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 bacterial activity occurs more slowly than the acid formation and an imbalance occurs. Intermediate volatile organic acids accumulate and the pH 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.

Note that 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 decrease rapidly at temperatures below 15°C and virtually ceases when water temperature drops below freezing (0°C). The pH 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 pH will upset methanogenic activity and inhibit pond performance. Alkalinity should range from 1000 to 5000 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 2000 mg/L.

Table 5.1 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 nitrogen (N) and phosphorus (P) must be available. Concentrations of inhibitory substances, including ammonia (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 1540 mg/L will result in severe toxicity, but concentrations of ammonium ion (NH_4^+) must be greater than 3000 mg/L to produce the same effect. Maintaining a pH of 7.2

TABLE 5.1
Ideal Operating Ranges for Methane Fermentation

Variable	Optimal	Extreme
Temperature (°C)	30 to 35	25 to 40
pH	6.8 to 7.4	6.2 to 7.8
Oxidation–reduction potential (MV)	–520 to –530	–490 to –550
Volatile acids (mg/L as acetic)	50 to 500	2000
Alkalinity (mg/L as CaCO ₃)	2000 to 3000	1000 to 5000

TABLE 5.2
Concentrations of Inhibitory Substances

Substance	Moderately Inhibitory (mg/L)	Strongly Inhibitory (mg/L)
Sodium	3500–5500	8000
Potassium	2500–4500	12,000
Calcium	2500–4500	8000
Magnesium	1000–1500	3000
Sulfides	200	>200

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011 (based on Parkin and Owen, 1986).

or below will ensure that most NH_3 will be in the form of NH_4^+ , so higher concentrations can be tolerated with little effect. Table 5.2 provides guidelines for acceptable ranges of other inhibitory substances.

Anaerobic ponds produce undesirable odors unless provisions are made to oxidize the escaping gases. Gas production must be minimized (the sulfate $[\text{SO}_4^{2-}]$ 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 to 0.9 meter (2 to 3 feet), so anaerobic activity at depth is not inhibited. Another option is to locate the pond in a remote area. Again, the problem with odors is not a problem until neighbors complain. For this reason, locating where there are no neighbors and thus no complaints is a huge benefit. A relatively long detention time is required for organic stabilization due to the slow growth rate of the CH_4 formers and sludge digestion. No matter where the anaerobic pond is located keep in mind that it should be constructed with a liner to avoid wastewater seepage into the groundwater.

5.2.3 ADVANTAGES AND DISADVANTAGES

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

uncomplicated. On the other hand, anaerobic ponds 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.

5.2.4 DESIGN CRITERIA

Design of anaerobic ponds is often based on organic loading rates, surface or volumetric loading rates, and hydraulic retention times (HRTs) derived from pilot plant studies and observations of existing operating systems. This is the case because the actual design is not well defined and there is no widely accepted overall design equation. 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 ratios ranging from 1:3 to 1:4, and maximum allowable seepage of 1 to 6 mm/day.

5.2.5 PERFORMANCE, OPERATION, MAINTENANCE, MODIFICATIONS, AND COSTS

System performance depends on loading, temperature, and whether the pH is maintained within the optimum range. Tables 5.3 and 5.4 show the expected removal efficiencies of municipal wastewaters. In cold climates, detention times as great as 50 days and volumetric loading rates as low as 0.04 kg BOD₅/m³/day may be required to achieve 50% reduction in BOD₅. Effluent total suspended solids (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.

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 to 10 years), depending on the amount of inert material in the influent and the temperature. Sludge depth should be measured annually. The primary costs associated with constructing an anaerobic pond are the cost of the

TABLE 5.3
BOD₅ Reduction as a Function of Detention Time
for Temperatures Greater than 20°C

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

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011 (based on WHO, 1987).

TABLE 5.4
BOD₅ Reduction as a Function of Detention Time and Temperature

Temperature (°C)	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

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011 (based on WHO, 1987).

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.

5.2.6 DESIGN MODELS AND EXAMPLE CALCULATIONS

Anaerobic treatment ponds are typically designed on the basis of volumetric loading rate and HRT. Although it is 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. In climates where the temperature exceeds 22°C, the following design criteria should yield a BOD₅ removal of 50% or better (WHO, 1987):

- Volumetric loading up to 300 g BOD₅/m³/day
- HRT of approximately 5 days
- Depth between 2.5 and 5 meters

In cold climates, detention times as great as 50 days and volumetric loading rates as low as 40 g BOD₅/m³/day may be required to achieve a 50% reduction in BOD₅.

5.3 FACULTATIVE PONDS

Facultative ponds are those in which a combination of anaerobic, aerobic, and facultative (able to growth in either the presence or absence of oxygen) bacteria stabilize effluents. The technology associated with conventional facultative ponds to treat municipal and industrial wastewater has been in widespread use in the United States for more than 100 years. These ponds are usually 1.2 to 2.4 meters (3.9 to 7.8 feet) in depth and are not mechanically mixed or aerated. The layer of water near the surface contains sufficient DO from atmospheric reaeration 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, carbon 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 pH of the near-surface water can exceed 10, creating conditions favorable for ammonia removal via volatilization. At night, when the algae are not photosynthesizing, O_2 levels decrease. Oxygen and pH 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 effluent quality may be reduced to the equivalent of primary effluent when an ice cover persists on the water surface. As a result, northern U.S. and Canadian provinces prohibit discharge from facultative ponds in the winter months.

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.

5.3.1 ADVANTAGES AND DISADVANTAGES

The advantages of facultative ponds include infrequent need for sludge removal and the 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.

5.3.2 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

required 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. Short-circuiting in a pond occurs because wastewater enters the pond in a non-uniform manner from the inlet to the outlet. It mixes and disperses. Some of the flow remains in the pond for the actual designed hydraulic retention time, but some leaves the pond rather quickly and thus short-circuits a significant amount of the treatment process. Pond short-circuiting is usually caused by thermal stratification, channeling directly from inlet to outlet, and wind effects. A multiple-cell system with at least four cells in series (i.e., influent wastewater flows into the primary cell, then to the secondary cell, and finally to the polishing cell before being discharged), with appropriate inlet and outlet structures, is strongly recommended to help alleviate this problem (Mara and Cairncross, 1989).

Most states have design criteria that specify the areal or surface organic loading rate expressed in kg/ha/day or lb/ac/day and the hydraulic loading rate expressed in m/day or ft/day residence time. Typical organic loading values range from 15 to 80 kg/ha/day. Detention times range from 20 to 180 days and can approach 200 days in northern climates where discharge restrictions prevail. Effluent $\text{BOD}_5 < 30$ 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 Gloyne (1976), Marais and Shaw (1961), Oswald (1968), 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 times 50% or less than the theoretical design value.

5.3.3 DESIGN METHODS

5.3.3.1 Areal Loading Rate Method

A series of detailed evaluations of facultative pond systems conducted by the U.S. Environmental Protection Agency (USEPA) remains a useful dataset for pond system performance in the United States (USEPA, 1975). Studies of systems in other countries have brought the literature up to date (Racault and Boutin, 2001; Kotsovinos et al., 2004; Oliveira and von Sperling, 2008; von Sperling and Oliveira, 2009). Table 5.5 presents 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 USEPA (Middlebrooks et al., 1982). Many of the design flaws in the systems referenced in Table 5.5 have been corrected since 1983.

TABLE 5.5
Design and Performance Data from USEPA Pond Studies

Location	Organic Load (kg BOD ₅ /ha/day)			Theoretical Detention Time			Months 30 mg/L Exceeded
	State	Design	Actual	State	Design	Actual	
	Design			Design			
Peterborough, NH	39.3	19.6	16.2	None	57	107	10, 2, 3, 4
Kilmichael, MS	56.2	43.0	17.5	None	79	214	11, 7
Endora, KS	38.1	38.1	18.8	None	47	231	3, 4, 8
Corrine, UT	45.0 ^a	36.2	29.7 ^a	180	180	70	None
			14.6 ^b			88 ^c	

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011 (based on Middlebrooks et al., 1982).

- ^a Primary cell.
- ^b Entire system.
- ^c Estimated from dye study.

These 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 BOD₅ loading rate range of 45 to 90 kg/ha/day is recommended. When the average winter air temperature ranges between 0 and 15°C, the organic loading rate should range between 22 and 45 kg/ha/day. For average winter temperatures below 0°C, the organic loading rates should range from 11 to 22 kg/ha/day.

A review of design standards in 2006 showed that most states have design criteria for organic loading and HRT for facultative ponds, with many now incorporating NH₃ conversion and P removal requirements. The principal changes since a survey by Canter and Englande (1970) are the nutrient removal requirements. The BOD₅ loading rate in the first cell is usually limited to 40 kg/ha/day or less, and the total HRT in the system is 120 to 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/day.

5.3.3.2 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 for the authors of this text to recommend one approach over the others. An evaluation of the design methods presented above, with operational data referenced in Table 5.5, 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 datasets have reached similar conclusions (Pearson and Green, 1995).

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% BOD₅ removal efficiency, and it assumes that solar energy for photosynthesis is above the saturated level. Provisions for removal outside this range are not anticipated; however, adjustments for other solar conditions can be calculated. Mara (1975) provided a detailed critique of the method.

5.3.4 PERFORMANCE, OPERATION MAINTENANCE, MODIFICATIONS, AND COSTS

Overall, facultative pond systems are simple to operate (we are not talking about rocket science here). However, simple to operate does not mean steady in performance; in fact, their performance is quite variable. BOD₅ removal can range up to 75%; TSS may exceed 150 mg/L; NH₃ removal can be significant (up to 90%), depending on temperature, pH, and detention time in the system, except in winter; approximately 50% phosphorus removal can be expected under high pH conditions; and pathogen 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.

Even with the potential odor problems, the trade-off (that is, if neighborly concerns can be ameliorated) for facultative ponds is that they are designed to operate by gravity flow, which means that the system requires less maintenance and has lower associated energy costs. The lower associated energy costs are due to no need (usually) for electrically powered pumps and other devices. 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. We discuss operation and maintenance requirements in detail later in the text.

In the operation of facultative wastewater ponds, various modifications to each process are not unusual. For example, a common modification is to operate them in the controlled-discharge mode, where discharge is prohibited during the winter months in cold climates 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 to serve as baffles to improve hydraulic conditions. Another modification uses a floating plastic grid to support the growth of duckweed (*Lemma* spp.) on the surface of the final cell in the pond system; the floating grid restricts light penetration and reduces algal growth (with sufficient detention time, >20 days), improving the final effluent quality. These types of modifications are discussed in detail later in the text.

Another variable in the construction and operation of facultative ponds is cost, which 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.

5.4 AERATED POND SYSTEMS

5.4.1 PARTIAL MIX AERATED PONDS

In aerobic wastewater treatment ponds, aerobic microorganisms use dissolved oxygen to degrade the organic matter into carbon dioxide, water, and cell biomass. With regard to dissolved oxygen, 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 required 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 meters 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% 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 to 4 kg O_2 /kW/hr, and mechanical surface aerators are rated at 1.5 to 2.1 kg O_2 /kW/hr. Consequently, diffused systems are somewhat more efficient than non-aerated ponds, but they require a significantly greater installation and maintenance effort.

Aerobic 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. It 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^- .

5.4.1.1 Advantages and Disadvantages

The advantages of aerobic ponds include reliable BOD_5 removal, significant nitrification of NH_3 with sufficient mean cell residence time, treatment of influent with higher BOD_5 in less space, and reduced potential for unpleasant odors. On the other hand, aerobic 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 offsite.

5.4.1.2 Design Methods

With the exception of a few innovations, the design of partial mix aerobic ponds is the same today as it was in the early 1980s. 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 (WEF, 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.

5.4.1.3 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 (meaning that the rate of treatment of a contaminant at any time is proportional to the contaminant concentration remaining at that time, a nonlinear relationship). Studies by Middlebrooks et al. (1982) showed 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 5.3 (Crites et al., 2006; Middlebrooks et al., 1982; Water Environment Federation, 2001).

$$\frac{C_e}{C_o} = \frac{1}{[1 + (kt/n)]^n} \quad (5.3)$$

where

C_e = Effluent BOD₅ concentration (mg/L).

C_o = Influent BOD₅ concentration (mg/L).

k = First-order reaction rate constant/day = 0.276/day at 20°C (assumed to be constant in all cells).

t = Total hydraulic retention time in pond system (days).

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:

$$\frac{C_n}{C_o} = \left(\frac{1}{1 + k_1 t_1} \right) \left(\frac{1}{1 + k_2 t_2} \right) \dots \left(\frac{1}{1 + k_n t_n} \right) \quad (5.4)$$

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

Mara (1975) showed 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.

5.4.1.4 Temperature Effects

The influence of temperature on the reaction is defined by Equation 5.5:

$$k_T = k_{20} \theta^{T_w - 20} \quad (5.5)$$

where

k_T = Reaction rate at temperature T /day.

k_{20} = Reaction rate at 20°C/day.

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):

$$T_w = \frac{AfT_a + QT_i}{Af + Q} \quad (5.6)$$

where

T_w = Pond water temperature (°C).

A = Surface area of pond (m²).

f = Proportionality factor = 0.5.

T_a = Ambient air temperature (°C).

Q = Wastewater flow rate (m³/day).

An estimate of the surface area is made based on Equation 5.4, corrected for temperature, and the temperature is calculated using Equation 5.6. After several iterations, when the water temperature used to correct the reaction rate coefficient agrees with the value calculated with Equation 5.6, the detention time in the system can be determined.

5.4.1.5 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/day at 20°C is recommended. 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 to 1.04 (Wang and Pereira, 1986).

5.4.1.6 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 5.1 and solving for t (all terms in this equation have been defined previously):

$$t = \left(\frac{n}{k} \right) \left[\left(\frac{C_o}{C_n} \right)^{1/n} - 1 \right] \quad (5.7)$$

5.4.1.7 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 5.8:

$$V = [LW + (L - 2sd)(W - 2sd) + 4(L - sd)(W - sd)] \left(\frac{d}{6} \right) \quad (5.8)$$

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., for a 3:1 slope, $s = 3$).

d = Depth of pond (m).

5.4.1.8 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 (1971, 1976), and Metcalf & Eddy (1991). 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. A schematic sketch of a static tube aerator is shown in Figure 5.1.

Surface aeration equipment is subject to potential icing problems in cold climates, but there are many options available to avoid this problem. 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 perforation, particularly in hardwater areas, and corrective action required purging with hydrochloric acid (HCl) gas. The final element recommended in this partial mix aerobic pond system is a settling cell with a 2-day HRT at the average design flow rate.

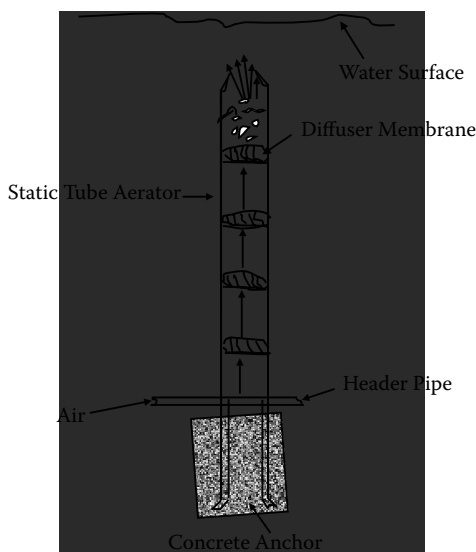


FIGURE 5.1 Static tube aerator. (Adapted from Reynolds, T.D. and Richards, P.A., *Unit Operations and Processes in Environmental Engineering*, 2nd ed., PWS Publishing, New York, 1996.)

5.4.1.9 Performance, Operation, Maintenance, Modifications, and Costs

Reliable BOD₅ removal up to 95% 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 NH₃ is less effective due to shorter detention times, but nitrification of NH₃ can occur in aerated ponds if the system is designed for that purpose. Phosphorus removal is only 15 to 25%. Removal of total and fecal coliform depends on length of detention time and temperatures. If effluent limits are <200 most probable number (MPN)/100 mL, disinfection may be needed.

With regard to limitations and O&M, there are several issues that must be taken into consideration and dealt with. For example, 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 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 and 2 W/m³ capacity, depending on the depth and configuration of the system. Modifications to aerobic ponds are routine. One physical modification is the use of plastic curtains supported by floats and anchored to the bottom to divide existing ponds into multiple cells or to serve as baffles to improve hydraulic conditions. A recently developed approach suspends a row of submerged diffusers for 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 with the system to improve performance. If there is sufficient depth for effective O₂ 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.

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.

5.4.2 COMPLETE MIX AERATED PONDS

Complete mix systems rely on mechanical aeration to introduce enough O₂ to completely degrade all BOD₅. In addition to that, however, the additional mixing suspends the solid material to enhance biodegradation.

5.4.2.1 Design Models and Pond Configuration

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. 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 retention times are generally less than 3 days, except where high-strength wastewaters are treated. An HRT range of 2 to 4 days is recommended so the microbial community has sufficient time to grow (von Sperling and de Lemos Chernicharo, 2005). 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 to 4:1 because the hydraulic flow pattern in complete mix systems actually more closely resembles the plug flow model.

5.4.2.2 Mixing and Aeration

The mixing requirements usually control the energy input required for complete mix pond systems. Several rational equations are available to estimate the O_2 requirements for pond systems. Complete mix systems are designed by estimating the strength of the BOD_5 entering the system and then calculating 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 5.9 is used to estimate O_2 transfer rates:

$$N = \frac{N_a}{\alpha \left[\frac{(C_{sw} - C_L)}{C_s} \right] (1.025)^{T_w - 20}} \quad (5.9)$$

where

N = Equivalent O_2 transfer to tapwater at standard conditions (kg/hr).

N_a = O_2 required to treat the wastewater (usually taken as $1.5\times$ the organic loading entering the cell) (kg/hr).

α = (O_2 transfer in wastewater)/(O_2 transfer in tapwater) = 0.9.

$C_{sw} = \beta(C_{ss})P$ = O_2 saturation value of the waste (mg/L), where β = (wastewater saturation value)/(tapwater O_2 saturation value); C_{ss} is the tapwater O_2 saturation value at temperature T_w ; and P is the ratio of barometric pressure at the pond site to barometric pressure at sea level (assume 1.0 for an elevation of 100 m).

C_L = Minimum DO concentration to be maintained in the wastewater (assume 2 mg/L).

C_s = O_2 saturation value of tapwater at 20°C and 1 atmosphere pressure = 9.17 mg/L.

T_w = Wastewater temperature ($^\circ\text{C}$).

Equation 5.6 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 four-cell system can be simulated by modifying the system using floating plastic partitions. There are several modifications or configurations of complete mix pond systems. Examples that will be discussed in Chapter 6 include the high-performance aerated pond systems and the BIOLAC® process.

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6 Pond Construction

6.1 INTRODUCTION

Using several bulldozers to dig a large hole in the ground and filling the hole with millions of gallons of water to form a pond, a lake, or a reservoir is not rocket science. It's easy; anyone can do it. However, if you are constructing an operational wastewater stabilization pond that must meet National Pollutant Discharge Elimination System (NPDES) permit requirements, a significant amount of engineering and design thought is required for proper construction. This is the case 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. Additionally, the biological factors affecting wastewater pond performance must be understood so that a reasonable estimate of the hydraulic retention time (HRT) required to achieve a specified efficiency is incorporated into the design. Nevertheless, 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 the operational ability to control the water level and discharge rate. These important physical design considerations are discussed in the following sections.

6.2 DIKE CONSTRUCTION

Erosion due to wind-driven water action or rain and rain-induced weathering is the major problem with maintaining wastewater stabilization dike structures. Other problems may be caused by burrowing animals. The key to successful pond and dike protection (that is, to providing a stable, reliable pond system) is the performance of proper maintenance, especially proactive preventive maintenance that anticipates problems before they occur.

6.2.1 EROSION 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 (Kays, 1986; USDOL, 2001; USEPA, 1977). Wave height is a function of wind velocity and fetch (the distance over which the wind acts on the water). The size of riprap required depends on the fetch length (Kays, 1986; Uhte, 1974). Riprap varies from river-run rocks that are 15 to 20 cm in size to quarry boulders that are 7 to 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 slope 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.

6.2.2 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, such ponds often have large sloped dike areas that cannot be protected in a more cost-efficient way. Ponds that have only minimum freeboard (i.e., the part of the reservoir above the maximum water elevation of the reservoir, with the freeboard distance being measured vertically) 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. In other cases, 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 is 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 with erosion control for cut-and-fill slopes should be used as a guide.

6.2.3 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 (Crites et al., 2006; USEPA, 1977). 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. Some provisions will often add to the expense of riprap placement for wave protection but can greatly reduce operation and maintenance expenses.

6.2.4 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 ensured 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 (Kays, 1986; Middlebrooks et al., 1978). Another method of preventing seepage where embankment material cannot be adequately compacted is placement of an impervious core in the levee with imported material.

6.3 POND SEALING

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. The criteria for lining a lagoon are highly dependent on the specific geographical location, on climate, on local hydrogeology, and on materials found in the lagoon wastewater.

6.3.1 SEEPAGE RATES

Because most regulatory agencies limit the amount of seepage from ponds, it is important to be able to estimate seepage rates. Stander et al. (1970) presented a summary of information (Table 6.1) on measured seepage rates in wastewater treatment ponds. Seepage rates in irrigation channels can be found in USDOJ (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

TABLE 6.1
Reported Seepage Rates from Pond Systems

Pond Base	Initial Seepage Rate		Hydraulic Load (m ³ /m ² /day)	Seepage Rate as Percent (%) of Hydraulic Load	Settling-In Period
	cm/day	m ³ /m ² /day			
Desert soil (sandy soil)	22.4	0.19	0.30	63	9 months
Sand and gravel	14.0	0.12	0.13	90	1 year
Sandy soil	—	—	—	—	Over 5 years, average
Clay loam and shale	—	0.13	0.05	Exceeded inflow rate	~1 year

Source: Adapted from Stander, R.Y., et al., in *Developments in Water Quality Research*, Shuval, H.I., Ed., Ann Arbor Science Publishers, Ann Arbor, MI, 1970.

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.

Field permeability tests indicated that 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., 1970).

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

TABLE 6.2
Seepage Rates for Various Liners^a

Liner Material	Maximum Expected Seepage Rate at 6 m of Water Depth after 1 Year of Service (cm/day)
Open sand and gravel	244
Loose earth	122
Loose earth plus chemical treatment	30.5
Loose earth plus bentonite	25.4
Earth in cut	30.5
Soil cement (continuously wetted, 10.2 cm)	10.2
Gunitite (3.8 cm)	7.6
Asphalt concrete (10.2 cm)	3.8
Unreinforced concrete (10.2 cm)	3.8
Compacted earth (91 cm)	0.76
Exposed prefabricated asphalt panels (1.3 cm)	0.08
Exposed synthetic membranes (0.11 cm)	0.003

Source: Adapted from Kays, W.B., *Construction of Linings for Reservoirs, Tanks, and Pollution Control Facilities*, John Wiley & Sons, New York, 1986.

^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.

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 nitrogen, phosphorus, 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 to 527 mg/L of chloride were observed.

A comparison of observed seepage rates for various types of liner material is presented in Table 6.2 (Kays, 1986). If an impermeable line 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). The equation is empirical and its use must be based on experience:

$$Q = \frac{4\sqrt{H}}{80} \quad (6.1)$$

where

Q = Maximum permissible leakage tolerance (L/min).

A = Lining area (m²).

H = Maximum water depth (m).

6.3.2 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 (Bhagat and Proctor, 1969; Seepage Control, Inc., 2005; Thomas et al., 1966). 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% and a silt content of 10%. Effectiveness increased with clay and silt content.

Four different soil columns were placed at the bottom of an animal wastewater pond to study the physical and chemical properties of soil and sealing of ponds (Chang et al., 1974; USDA, 1972). It was discovered that the initial sealing that 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.

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 alternating 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. The most commonly used slats for chemical sealing have been sodium polyphosphates, sodium carbonate, and sodium chloride.

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/day. After 2 weeks of manure water addition, infiltration averaged 5.8 cm/day; after 4 months, it was 0.5 cm/day.

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/day seepage rate dropped to 0.56 cm/day after 3 months and to 0.30 cm/day after 6 months.

6.3.3 DESIGN AND CONSTRUCTION PRACTICE

6.3.3.1 Types of Lining Materials

A general presentation of recommended pond sealing design and construction procedures is provided in this section. 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 types of material selected, there are many common design, specification, and construction practices. A summary of the effective design practices in a cut-and-fill reservoir is provided below. A cut-and-fill reservoir is constructed by excavating the central portion of the area and then utilizing the excavated material as fill material for the embankment. Even if the earth from the hole is not used in the embankment, the facility is still referred to as a cut-and-fill reservoir. Most of these practices are common-sense observations, yet experience shows that these practices are very often ignored.

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

1. The design and construction of liners should be carried out by trained, experienced professionals.
2. Lining must be placed on a stable soil foundation or structure.
3. 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.
4. A leakage tolerance should be included in the specifications.
5. Continuous, thin, impermeable-type linings should be placed on a smooth surface of concrete, earth, gunite, or asphalt concrete.
6. 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.
7. Formal or informal anchors may be used at the top of the slope.
8. Inlet and outlet structures must be sealed properly.
9. All lining punctures and cracks in the support structure should be sealed.
10. Emergency discharge quick-release devices should be provided in large reservoirs.
11. Wind problems with exposed thin membrane liners can be controlled by installing vents so they are built into the lining.
12. Adequate protective fencing must be installed to control vandalism.

6.3.3.2 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 sections include consideration of the materials, costs, evaluations of durability, and effectiveness in limiting seepage. The cost analysis is somewhat arbitrary, as it depends primarily on the availability of the materials.

6.3.3.2.1 Bentonite

Bentonite is a type of clay (sodium montmorillonite) formed from altered volcanic ash. Most types of bentonite swell when they absorb water. In addition to exhibiting at high degree of swell, bentonite also exhibits 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% 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/m².
- 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 to 5 cm thick and covered with a 20- to 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 to 10 cm in thickness is placed on the reservoir bottom and covered with a protective cover of sand or soil. This method requires about 13.5 kg/m of bentonite.

For 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 subgrade surface should be dragged to remove large rocks and sharp angles. Usually two passes with adequate equipment are sufficient to smooth the subgrade.
- The subgrade should be rolled with a smooth steel roller.
- The subgrade 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 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 hardwater 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 a No. 30 sieve then it should be well graded. Bentonite should contain a moisture content of less than 20%. 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 subgrade 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 absorbed 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 2 to 4 years. A buried bentonite blanket may last from 8 to 15 years (USDA, 2010; USEPA, 1978). Seepage losses through buried bentonite blankets are approximately 0.2 to 0.25 m³/m²/day. This figure is for thin blankets and represents about a 60% improvement over ponds with no lining.

6.3.3.2.2 Asphalt

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

- *Asphalt membrane*—This 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 asphalt membrane, above, except that a gravel-sand cover is applied over the asphalt 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 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/m² 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/m². 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 materials 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 3 to 4 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 to 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 (USDOI, 2001). Preparation of the subgrade 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, as 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. Hot applied buried asphalt membranes provide some of the tightest linings available. These linings last longer than other flexible membrane linings. Asphalt linings composed of prefabricated buried material are best for small jobs, as 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 material 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 $0.02 \text{ m}^3/\text{m}^2/\text{day}$ ($2.3 \times 10^{-7} \text{ cm/sec}$). Asphalt membrane linings can be constructed at any time of the year, but fall and winter installation may dictate 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 subgrade material
- Cleaning operations
- Scour of cover material membrane puncture

6.3.3.2.3 Soil Cement

Soil cement is produced from a mixture of soil, cement, and water. 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 7 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 2 to 6% 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 cement modified soil. Soil cement has been used successfully in some cases in mild climates. Where wetting or drying is a factor, or if freeze–thaw cycles are present, the lining will deteriorate rapidly (USDOI, 2001).

6.3.3.2.4 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 which simplifies installation, and are 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 wastewater 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,” “waterproofing,” or “membranes” will yield the most current information. Kays (1986) presented several detailed drawings showing the correct method for the application of linings; manufacturers’ literature is another good source of information. The prudent design engineer will consult these sources before designing and installing a liner.

The most difficult design problem encountered in liner application includes 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 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) recommended 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, 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.

6.3.3.3 Mechanisms of Failure

When a public service entity or owner of a wastewater stabilization pond operation asks the planner, designer, engineer, and installer how much the installation of a liner will cost, many of the key people involved with installation simply scratch their collective heads and begin to ask questions of their own. For example, these key installation personnel might ask: "What type of liner do you want? How will the liner be used? What is the expected life expectancy? What safety features are to be included? And, finally, what color, style, and model do you want?" In other words, specifications must be provided by the operator or owner or both before any of these questions can be answered. One question that can never be answered completely with 100% accuracy is "What is the risk failure of the liner installation?" It is interesting to note that when Kays (1986) classified the principal types of failures observed in cut-and-fill reservoirs, his list was extensive, and case histories involving all of the categories are also extensive. However, the most frequently observed failure mechanisms were a 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. Moreover, operational failures can be caused by a lack of regular cleaning, reverse hydrostatic uplift, vandalism, and seismic activity. And then there are mechanical failures, such as field seam failure, structure seal failure, bridging, and separation of butyl-type cured sheets at the joint due to unequal tension between the sheets. In general, unless a protective cover is provided, it is advisable to use reinforced membranes or thick materials recommended for exposure to the elements, including weather-related events such as wind, wave erosion, and ozone damage.

6.3.3.4 Cover Materials

The cost of linings for ponds varies with the type and 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. A material such as 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, deterioration, and damage caused by animals and pond cleaning, as well as weed control. 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, or there are extremes in climatic conditions.

6.4 POND HYDRAULICS

In Chapter 1 of this book we presented a discussion on what we termed *still waters*. The purpose of this still water discussion is multifaceted but primarily it is designed to point out that what we think we see and what we think we know about a stream pool or pond by simple observation of it from the surface is not necessarily what we are truly seeing or truly understanding. Recall the following excerpt from that earlier presentation and view it as a brief summary of what we actually see and observe and understand when viewing a river pool from its surface only:

Then the reality check: This stillness, like all feelings of calm and serenity, could be fleeting, momentary, temporary, you think. And you would be correct, of course, because there is nothing still about a healthy river pool.

“There is nothing still about a healthy river pool.” We extend this statement herein to include: “There is nothing still about a healthy, properly operated wastewater stabilization pond.” This is not to say that we do not understand what is going on, what is happening in the murky confines of a wastewater stabilization pond. We do understand. Well, we understand to a point, that is. In pond hydraulics, for example, we have gained a large amount of information via pilot testing and general experience regarding what occurs inside the wastewater stabilization pond. We have learned what inputs and influences affect pond hydraulics; however, keep in mind that current understanding of some of these inputs and influences is still very limited. The truth is this is one of those classic situations where we don’t know what we don’t know about exactly what occurs within the wastewater stabilization pond.

One thing is certain; we cannot get close to understanding what we do know or do not know about wastewater stabilization ponds unless we have a basic understanding of the issues and the terminology involved. To aid in this important undertaking, we refer readers to the work of Shilton and Harrison (2003), arguably the top team of experts in the field of pond hydraulics. In the meantime, we broadly include here consideration of inputs and influences on the flow momentum within a pond and definitions (Shilton and Harrison, 2003, p. 8):

- *Flow rate*—Higher flow rates increase inlet momentum.
- *Inlet size*—Smaller inlets increase the inlet velocity and so also the inlet momentum.

- *Inlet position and orientation*—These factors define the way the inlet momentum is introduced into the main body of the pond and as a result influence the main flow pattern.
- *Outlet position*—This determines the distance from the inlet and, therefore, the time for the main flow to reach the outlet.
- *Pond geometry and baffles*—These have a strong influence on flow patterns and define the degree of channeling.
- *Temperature/density effects*—These may influence the channeling and circulation of the main flow.
- *Wind shear*—Higher wind velocities and greater pond surface areas increase the momentum inputted and as a result influence the main flow pattern.
- *Mechanical aerators*—If present, these are a significant momentum input and as a result can have a strong influence on the main flow pattern.

6.4.1 INLET AND OUTLET CONFIGURATIONS

In the past, the importance of the position and design of an inlet in a waste stabilization pond was ignored, considered to be insignificant, or not considered at all. 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 have shown that the use of centralized inlet structures is an inefficient method of introducing waste to a pond, often resulting in less than ideal residence time (Crites et al., 2006; Ewald, 1973; Finney and Middlebrooks, 1980; Mangelson, 1971; Mangelson and Watters, 1972; Middlebrooks et al., 1982; Shilton, 2005). Multiple inlet arrangements are preferred, even in small ponds (<0.5 ha) and preferably by means of a log 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. The inlet position and its relation to the outlet are important. Pearson et al. (1995) concluded that “the positioning and depths of the inlet and outlets may have a greater beneficial impact on treatment efficiency than pond shape” (p. 137). Outlet structures should be designed for multiple depth withdrawal, and all withdrawals should be a minimum of 0.6 m below the water surface.

Traditional thinking has been based on the assumption that wastewater moves directly from the pond inlet toward the outlet. It has been shown, however, “that horizontal inlets [see Figure 6.1] can drive the pond contents to circulation in large cells at velocities much faster than if the flow was simply moving from inlet to the outlet in a ‘plug flow’ manner” (Shilton and Harrison, 2003, p. 137). The jetting effect from an inlet pipe is localized, but it still provides a consistent source of momentum in a fixed direction at a fixed point and then transfers the momentum to the bulk volume

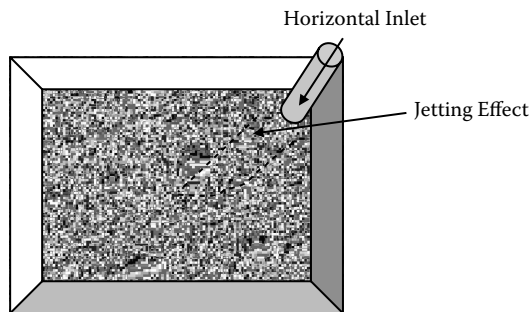


FIGURE 6.1 Jetting effect of the pond inlet.

driving the main circulation (see Figure 6.1). It is interesting to note that experiments using larger diameter horizontal inlet piping have not shown significant improvement in delaying short-circuiting in ponds.

The following depths are recommended for pond outlets (Mara and Pearson, 1998):

- Anaerobic ponds, 300 mm (~1 ft)
- Facultative ponds, 600 mm (~3 ft)

In anaerobic ponds, the outlet should be deep enough to avoid any surface crust. In facultative ponds, the depth is selected so as to discharge from below the maximum depth of the algal band (Shilton and Harrison, 2003). If an outlet weir is to be used, as opposed to a simple outlet pipe, then this should incorporate a scum guard that extends to the indicated depth. In maturation ponds, where “algal bands are irrelevant” (Mara and Persona, 1998, p. 62), the outlet should be located close to the surface.

6.4.1.1 Pond Transfer Inlets and Outlets

Pond transfer inlets and outlets should be constructed to minimize head loss at peak recirculation rates, ensure 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. Transfer pipes should be numerous and large enough to limit peak head loss to about 7 to 10 cm with pipes flowing about two-thirds to three-quarters full. Supply and return channel sizing should ensure 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 ensured. By operating with the transfer pipes less than full, an 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 are usually made of plastic pipe or bitumastic-coated, corrugated metal pipe, and they 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 ensure easy boat access for sampling, aquatic plant control, and pond maintenance.

6.4.2 BAFFLING

Better treatment is obtained when the flow is guided through the pond. Baffles are commonly used to improve the hydraulic and treatment efficiency and esthetics of a pond. Simply put, baffles are known to improve pond performance. Baffle structures do not have to be particularly strong because there is little horizontal force on baffling except that caused by wave action. 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. Persson (2000) investigated the use of sub-surface berms or islands (in effect, baffles) located close to the inlet. He found that these resulted in a reduction of inlet jet. Commercial float-submerged plastic baffling for ponds is also available. Regardless of the design or type of baffling used, it is important to ensure that the baffle is well sealed and does not leak effluent from one side to the other to avoid any short-circuiting. 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. Be advised that winter ice can damage or destroy baffles in cold climates.

6.4.3 WIND EFFECTS

Observation and experiment (and a dose of common sense) clearly demonstrate that wind generates a circulatory flow in bodies of water. It is generally believed, because of the perceived improvement in aeration and mixing, that wind provides a positive influence on ponds. Two main mechanisms provide oxygenation in pond systems: mass diffusion for the atmosphere and oxygen production by algae with the pond. It is not unusual to assume that natural atmospheric and mechanical conditions cause the largest increase in pond oxygenation; however, it is the algal population that is most proficient, productive, and significant. The truth is the aeration provided by wind mixing is not as important as is commonly assumed. It has been observed that wind may create flow patterns in ponds that encourage short-circuiting issues. To minimize short-circuiting due to wind, the pond inlet–outlet axis should be aligned perpendicular to the prevailing wind direction. If 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 the direction of the wind and the return inflow is in the upwind direction along the bottom.

6.4.4 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). Stratification is a density-induced separation of the pond into layers (these layers may be identified by different temperature, oxygen, and redox measurements). The result of a stratified inflow layer 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 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 utilities 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, although clogging of openings with solid material could be a problem (USEPA, 2011).

6.5 POND RECIRCULATION AND CONFIGURATION

Pond recirculation involves inter- and intrapond recirculation as opposed to mechanical mixing in the pond cell. The effluents from pond cells are mixed with the influent to the cells. In intrapond recirculation, effluent from a single cell is returned to the influent to that cell. In interpond recirculation, effluent from another pond is returned and mixed with influent to the pond (Figure 6.2). 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 intrapond 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 biochemical oxygen demand (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 dissolved oxygen (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

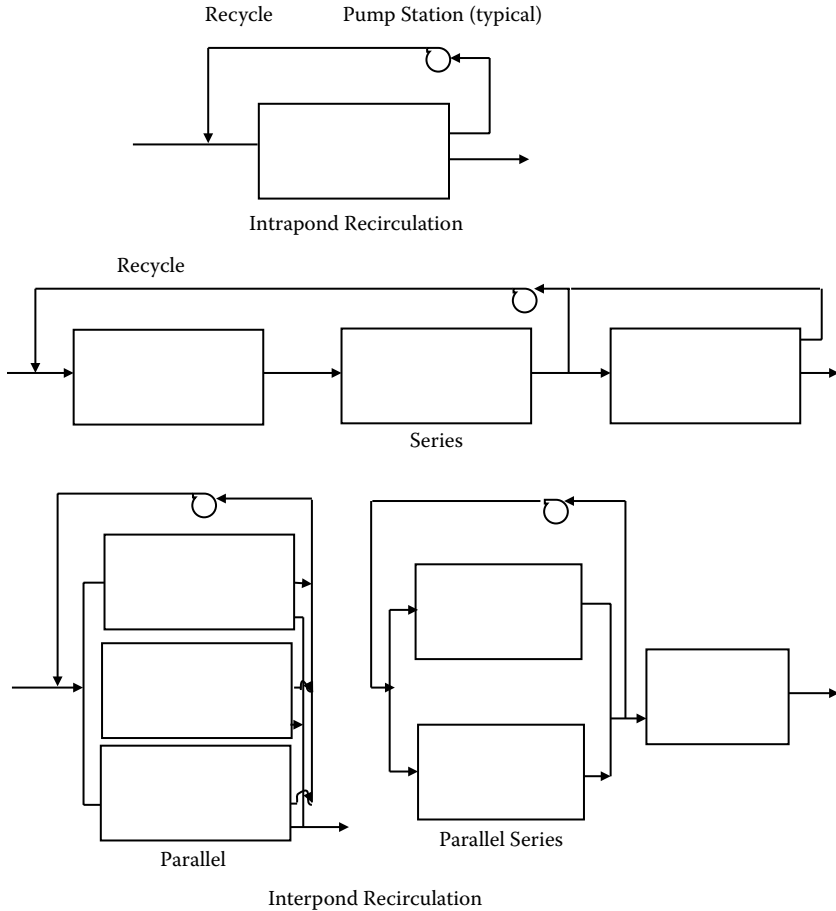


FIGURE 6.2 Common pond configurations and recirculation systems.

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 nighttime 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 6.2 (USEPA, 2011).

6.5.1 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/day) 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

$$t = \frac{V}{(1+r)Q} \quad (6.2)$$

where

t = Time.

V = Volume of pond cell.

r = Recycle flow rate.

Q = Influent flow rate.

r/Q = Recycle ratio.

Another effect of recirculation in the series configuration is a reduction in the BOD_5 in the mixture entering the pond, as given by the following expression:

$$S_m = \frac{S_{in}}{(1+r)} + \left[\frac{r}{(1+r)} \right] S_e \quad (6.3)$$

where

S_m = BOD_5 of the mixture.

S_{in} = Influent BOD_5 .

r = Recycle flow rate.

S_e = Effluent BOD_5 from the third cell.

S_m would be only 20% of S_{in} with a 4:1 recycle 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.

6.5.2 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, in series or parallel. In the parallel configuration, the surface loading (kg BOD_5 /ha/day) 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 a parallel configuration.

Based upon the analyses of performance data from selected aerated and facultative ponds, four ponds in series give the best BOD₅ and fecal coliform removal for ponds designed as plug flow system. 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. 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 to 1.2 m. Multiple- or variable-speed pumps are used to adjust the recirculation rate to seasonal load changes.

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7 Advanced Pond Design

7.1 INTRODUCTION

To this point, we have discussed the basic design of wastewater treatment ponds. In this chapter, we discuss design innovations that have come about through a better understanding of the biological processes occurring in these systems and experience building them under different environmental conditions. Many of these innovations have allowed communities to retain their pond systems with modifications rather than abandoning them in favor of mechanized systems (USEPA, 2011). Examples include fermentation pits in facultative ponds to protect anaerobic digestion, streamlined footprints, improved aerators or mixers, and the addition of covers to retard algal growth in polishing ponds.

7.2 ADVANCED INTEGRATED WASTEWATER POND SYSTEM® (AIWPS®)

The Advanced Integrated Wastewater Pond System® (AIWPS®) has evolved over the past 50 years as a result of research carried out by Dr. William J. Oswald at the University of California, Berkeley, and other locations (Oswald, 1977; Oswald and Green, 2000). The majority of the research and operations experience has involved facilities in areas with moderate climates. Certain aspects of the process are currently patent protected, with new patents pending. The salient features of the patents reflect the evolution of the design, including a smaller land footprint, an increased depth in the primary pond, and appropriately sized aperture for the in-pond digesters (IPDs).

Typically, the AIWPS technology consists of compacted earthen dikes, such as those used in conventional pond systems, with a minimum of four types of ponds in series. These separate unit processes in the treatment scheme reduce the impact of short-circuiting in the ponds and provide for depth control in areas where evaporation exceeds precipitation. Although the unit processes in AIWPS do not differ from those in conventional wastewater treatment pond systems (i.e., primary sedimentation, flotation, anaerobic digestion, methane fermentation, aeration, photosynthetic oxygenation, nutrient removal, secondary sedimentation, nutrient removal, storage, and final disposal or reclamation and reuse), their application and some patented design features do differ from those in most conventional pond systems. Figure 7.1 is a plan view of what is called a Type 1 AIWPS facility.

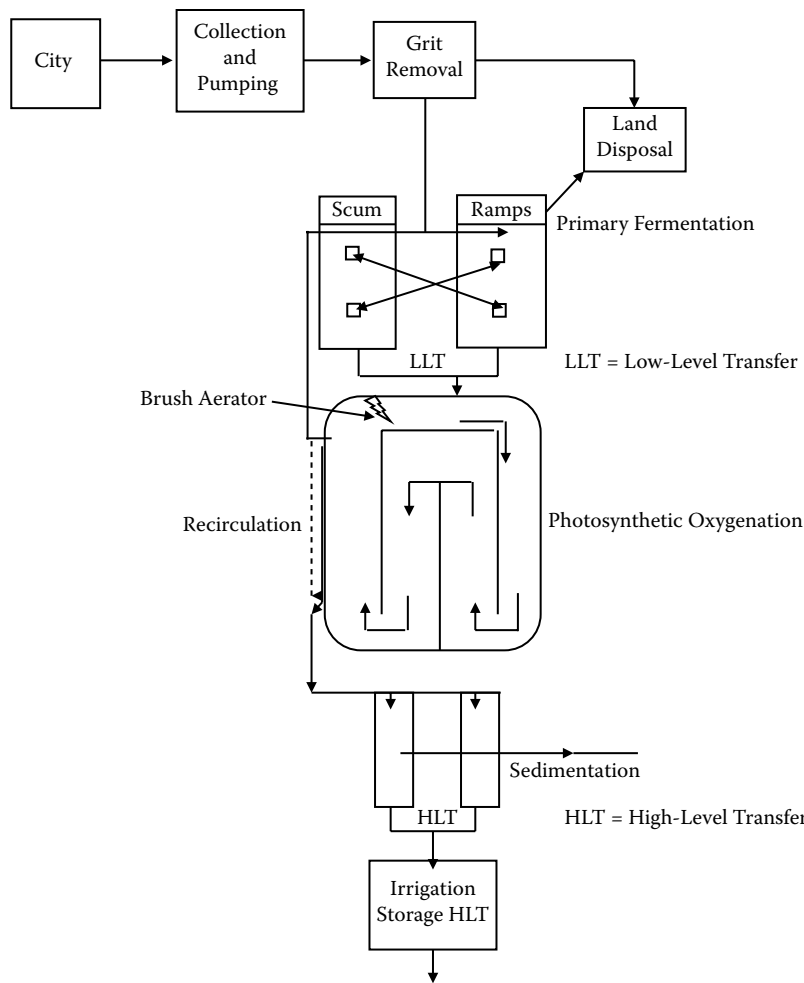


FIGURE 7.1 Type I Advanced Integrated Wastewater Pond System®. (From USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, EPA 600/R-11/088, U.S. Environmental Protection Agency, Washington, DC, 2011.)

The first pond in the series is an advanced facultative pond (AFP), a unique feature of an AIWPS facility. The AFP contains deep anaerobic digestion and methane fermentation pits with a minimum depth of 6 to 8 m through which all of the influent wastewater upflows. Figure 7.2 shows a schematic cross-section of the AFP. The great depth and certain design elements prevent dissolved oxygen (DO) from entering the fermentation pit or IPD, thereby improving methane fermentation and reducing solids transfer to subsequent ponds. Most settleable solids are retained in the pit and undergo anaerobic digestion and methane fermentation. The overflow velocity is limited to

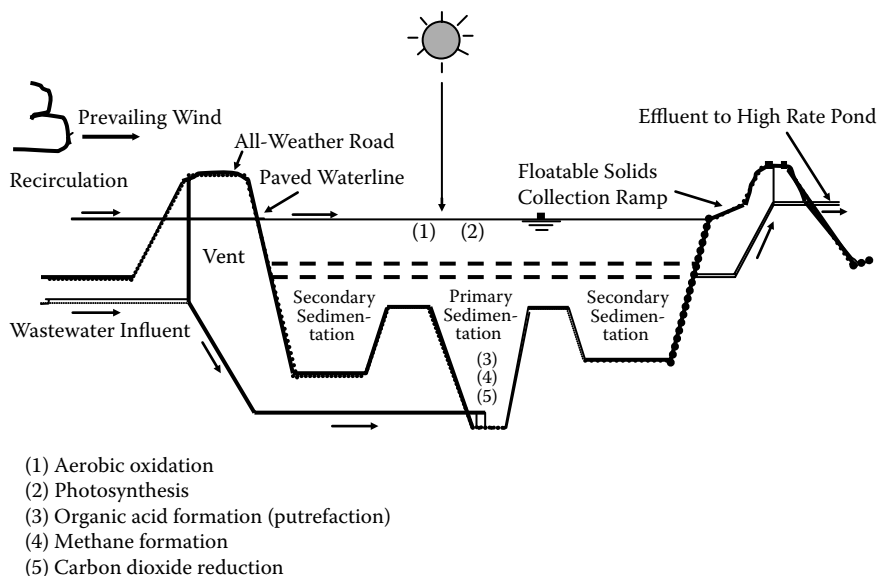


FIGURE 7.2 Cross-section of primary facultative pond of an Advanced Integrated Wastewater Pond System®. (Adapted from Oswald, W.J., *A Syllabus on Advanced Integrated Pond Systems*®, University of California, Berkeley, 1996.)

less than 2.0 m/day to optimize sedimentation and to prevent most helminth ova and ova cysts from leaving the fermentation pit. Sludge fermentation has been shown to be sufficiently complete to essentially eliminate sludge handling in moderate climates for many decades. A public works budget should maintain a line item for removal activities for when it will be necessary to remove sludge, and a plan should be in place to compost it, preferably onsite. Limited data are available for cold climate operation, but indications are that fermentation occurs in areas with weather as severe as that in the high country of the Rocky Mountains. Floatables are collected on a downwind concrete scum ramp and removed periodically. An AFP will reportedly remove at least 60% of the influent BOD_5 and a greater percentage of total suspended solids (TSS). In the southwestern United States, removals up to 80% have been observed. Outlets from the AFP are located 1 to 1.3 m below the surface to prevent discharge of floatables into the secondary pond. Recirculation of algal-laden waters with levels of O_2 and supplementary mechanical aeration controls odors.

The second pond in series may be a secondary facultative pond (SFP) or a high-rate pond (HRP), depending on the desired level of treatment. Figure 7.3 shows a schematic drawing of the raceway in the HRP. The HRP is used to produce high concentrations of algae and DO. With recirculation, the DO can be used for odor control at the surface of the AFP. The algae remove nutrients and can also serve useful purposes (Woertz et al., 2009). HRP systems are usually less than a meter in depth and are mixed with low-speed paddle-wheel mixers (brush aerators in Figure 7.1) at a mean surface velocity of approximately 15 cm per second. The elevated pH in the

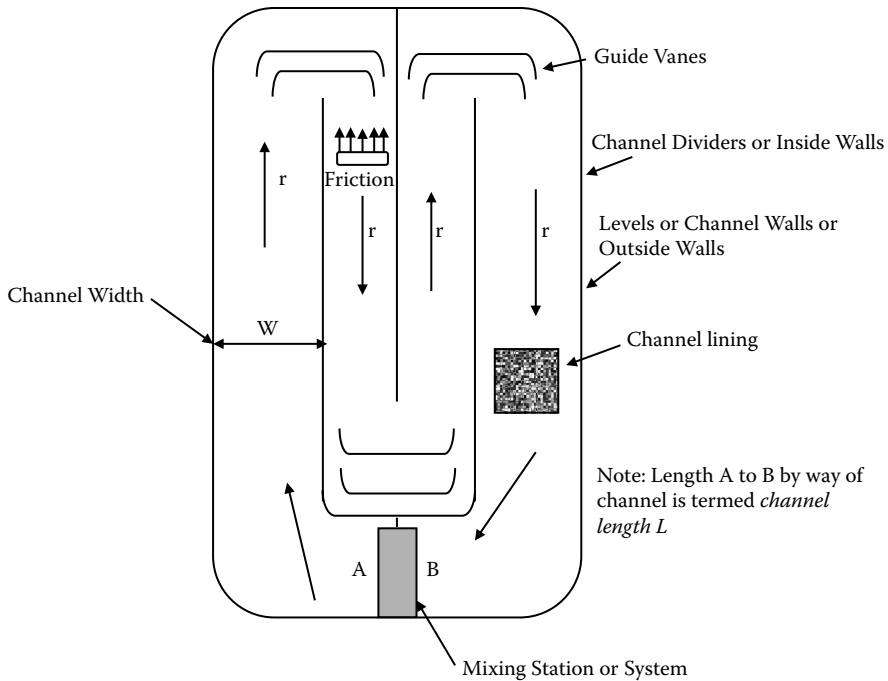


FIGURE 7.3 Schematic of raceway to cultivate microalgae for O_2 production. (Adapted from Oswald, W.J., *A Syllabus on Advanced Integrated Pond Systems*®, University of California, Berkeley, 1996.)

HRP along with the intensity of the sunlight it receives contribute to maintaining high kill rates of bacteria present in the influent. These high pH values and temperatures in the summer contribute to NH_3 (ammonia) removal from the wastewater by volatilization, although this is not the only NH_3 removal mechanism. Effluent from the HRP is withdrawn from the surface to obtain the highest quality water with high DO concentrations and high pH values.

Chlorination of effluent from AIWPS systems is not recommended because of low most probable number (MPN) counts in the effluent and the fact that chlorine doses above 10 mg/L are required to kill algae, potentially releasing their nutrients and biochemical oxygen demand (BOD_5) back into the water column (Oswald, 1996). However, it is likely that many states will still require chemical disinfection of these effluents, and if such a requirement is set then algae should be removed prior to chlorination. Algae can tolerate ozone disinfection.

The third pond is used for algal sedimentation and collection for drying, while the fourth is for storage, further disinfection, and TSS removal. In areas where advanced treatment may not be feasible and human contact is expected, deep maturation ponds with detention times of 10 to 20 days following treatment in an AFP, a HRP, and an algae settling pond (ASP) in series will provide reliable control of pathogenic microorganisms of human origin.

With regard to pond modifications, the Type 2 AIWPS modification provides supplementary aeration to replace algae as the source of DO in the primary pond surface. The primary pond (AFP) is designed exactly the same as the primary pond in the Type 1 AIWPS. Type 2 AIWPS facilities require less land but more energy for mechanical aeration. Where land costs are not a limiting factor, the concept is well suited for the treatment of municipal wastewater and biodegradable industrial and agricultural wastewaters. New configurations of the design have reduced the footprint and thus the land requirements.

7.2.1 ADVANTAGES AND DISADVANTAGES

The advantages of the AIWPS technology are reliable treatment, much reduced need for sludge disposal, and lower energy and land requirements, all of which result in considerable cost reductions for operation and maintenance. Additional information about the process and operational data are available in Downing et al. (2002), Green et al. (1995a,b, 1996, 2003), Nurdogan and Oswald (1995), Oswald (1990a, 1995b, 1996, 2003), Oswald et al. (1994), and USEPA (2000). Another advantage of the AIWPS technology is the ability of the sludge blanket to retain parasite eggs (ova), adsorb toxic materials, and convert organic nitrogen into N_2 . Toxicity tests conducted over 40 years have demonstrated that the AIWPS is able to produce an effluent from municipal or industrial wastewaters that will satisfy most regulatory requirements. One disadvantage of the AIWPS technology is that land is required for disposal of the effluent at certain times of the year to remove algae from the effluent. If there is no recirculation of the settling pond effluent, odors may be present in the advanced facultative pond. The use of surface mechanical aeration in the primary pond at those times will correct the situation.

7.2.2 DESIGN CRITERIA AND PERFORMANCE

Design criteria can be obtained in Oswald (1996), and further information can be found in Crites et al. (2006). The exact number of operating AIWPS systems is unknown, but many are in operation around the world. Four complete full-scale AIWPS units have been closely studied in California, and large-scale pilot units have been built and studied in the Philippines, Australia, Tunisia, Kuwait, South Africa, France, Indonesia, Thailand, Morocco, and Spain. Detailed descriptions of various AIWPS facilities, including wastewater treatment facilities similar to Type II AIWPS facilities (i.e., they do not include the high-rate algal growth and settling ponds), are presented in USEPA (2011).

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8 Nutrient Removal

8.1 INTRODUCTION

Modern conventional wastewater treatment plants already have incorporated or are in the process of incorporating biological nutrient removal (BNR) to remove nutrients, total nitrogen, and total phosphorus from the wastestream while it is being treated and before being outfallen to the receiving water body. Nitrogen and phosphorus are the primary causes of cultural eutrophication (i.e., nutrient enrichment due to human activities) in surface waters. The most recognizable manifestations of this eutrophication are algal blooms that occur during the summer. Chronic symptoms of over-enrichment include low dissolved oxygen, fish kills, murky water, and depletion of desirable flora and fauna. In addition, the greater levels of algae and turbidity increase the need to chlorinate drinking water, which, in turn, leads to higher levels of disinfection byproducts that have been shown to increase the risk of cancer (USEPA, 2007c). Excessive amounts of nutrients can also stimulate the activity of microbes, such as *Pfisteria*, which may be harmful to human health (USEPA, 2007d).

Approximately 25% of all water body impairments are nutrient related (e.g., nutrients, oxygen depletion, algal growth, ammonia, harmful algal blooms, biological integrity, turbidity) (USEPA, 2007d). In efforts to reduce the number of nutrient impairments, many point-source discharges have received more stringent effluent limits for nitrogen and phosphorus. To achieve these new, lower effluent limits, facilities have begun to look beyond traditional treatment technologies.

Recent experience has reinforced the concept that biological nutrient removal systems are reliable and effective in removing nitrogen and phosphorus. The process is based on the principle that, under specific conditions, microorganisms will remove more phosphorus and nitrogen than is required for biological activity; thus, treatment can be accomplished without the use of chemicals. Not having to use and therefore having to purchase chemicals to remove nitrogen and phosphorus potentially has numerous cost-benefit implications. In addition, because chemicals are not required to be used, chemical waste products are not produced, reducing the need to handle and dispose of waste. Several patented processes are available for this purpose. Performance depends on the biological activity and the process employed.

8.1.1 BIOLOGICAL NUTRIENT REMOVAL

Biological nutrient removal removes total nitrogen (TN) and total phosphorus (TP) from wastewater through the use of microorganisms under various environmental conditions in the treatment process (Metcalf & Eddy, 2003).

TABLE 8.1**Mechanisms Involved in the Removal of Total Nitrogen**

Form of Nitrogen	Common Removal Mechanism	Technology Limit (mg/L)
Ammonia nitrogen	Nitrification	<0.5
Nitrate nitrogen	Denitrification	1–2
Particulate organic nitrogen	Solids separation	<1.0
Soluble organic nitrogen	None	00.5–1.5

Source: USEPA, *Biological Nutrient Removal Processes and Costs*, U.S. Environmental Protection Agency, Washington, DC, 2007 (based on Jeyanayagam, 2005).

8.1.1.1 Nitrogen Removal

Total effluent nitrogen is comprised of ammonia, nitrate, particulate organic nitrogen, and soluble organic nitrogen. The biological processes that primarily remove nitrogen are nitrification and denitrification (Jeyanayagam, 2005). During nitrification, ammonia is oxidized to nitrate by one group of autotrophic bacteria, most commonly *Nitrosomonas*. Nitrite is then oxidized to nitrite by another autotrophic bacteria group, the most common being *Nitrobacter*. Denitrification involves the biological reduction of nitrite to nitric oxide, nitrous oxide, and nitrogen gas. Both heterotrophic and autotrophic bacteria are capable of denitrification. The most common and widely distributed denitrifying bacteria are *Pseudomonas* species, which can use hydrogen, methanol, carbohydrates, organic acids, alcohols, benzoates, and other aromatic compounds for denitrification (Metcalf & Eddy, 2003).

In BNR systems, nitrification is the controlling reaction because ammonia-oxidizing bacteria lack functional diversity, have stringent growth requirements, and are sensitive to environmental considerations (Jeyanayagam, 2005). Note that nitrification by itself does not actually remove nitrogen from wastewater; rather, denitrification is needed to convert the oxidized form of nitrogen (nitrate) to nitrogen gas. Nitrification occurs in the presence of oxygen under aerobic conditions, and denitrification occurs in the absence of oxygen under anoxic conditions (USEPA, 2007c). Table 8.1 summarizes the removal mechanisms applicable to each form of nitrogen. Note that organic nitrogen is not removed biologically; rather, only the particulate fraction can be removed through solids separation via sedimentation or filtration.

8.1.1.2 Phosphorus Removal

Total effluent phosphorus is comprised of soluble and particulate phosphorus. Particulate phosphorus can be removed from wastewater through solids removal. To achieve low effluent concentrations, the soluble fraction of phosphorus must also be targeted. Table 8.2 shows the removal mechanisms for phosphorus.

Biological phosphorus removal relies on phosphorus uptake by anaerobic heterotrophs capable of storing orthophosphate in excess of their biological growth requirements. The treatment process can be designed to promote the growth of these organisms, known as phosphate-accumulating organisms (PAOs), in mixed liquor. Under anaerobic conditions, PAOs convert readily available organic matter, such as volatile fatty

TABLE 8.2
Mechanisms Involved in the Removal of Total Phosphorus

Form of Phosphorus	Common Removal Mechanism	Technology Limit (mg/L)
Soluble phosphorus	Microbial uptake	0.1
	Chemical precipitation	
Particulate phosphorus	Solids removal	<0.05

Source: USEPA, *Biological Nutrient Removal Processes and Costs*, U.S. Environmental Protection Agency, Washington, DC, 2007 (based on Jeyanayagam, 2005).

acids (VFAs), to carbon compounds called polyhydroxyalkanoates (PHAs). PAOs use energy generated through the breakdown of polyphosphate molecules to create PHAs. This breakdown results in the release of phosphorus (WEF et al., 2006).

Under subsequent aerobic conditions in the treatment process, PAOs use the stored PHAs as energy to take up the phosphorus that was released in the anaerobic zone, as well as any additional phosphate present in the wastewater. In addition to reducing the phosphate concentration, the process renews the polyphosphate pool in the return sludge so the process can be repeated. Some PAOs use nitrate instead of free oxygen to oxidize stored PHAs and take up phosphorus. These denitrifying PAOs remove phosphorus in the anoxic zone rather than the aerobic zone (Jeyanayagam, 2005).

As shown in Table 8.2, phosphorus can also be removed from wastewater through chemical precipitation. Chemical precipitation primarily uses aluminum and iron coagulants or lime to form chemical flocs with phosphorus. These flocs are then settled out to remove phosphorus from the wastewater. However, compared to biological removal of phosphorus, chemical processes have higher operating costs, produce more sludge, and result in added chemicals in sludge (Metcalf & Eddy, 2003). When total phosphorus levels close to 0.1 mg/L are needed, a combination of biological and chemical processes may be less costly than either process by itself.

8.2 NUTRIENT REMOVAL IN WASTEWATER TREATMENT PONDS

Although the reliability of pond systems to remove BOD₅ and suspended solids is well documented, until recently little consideration has been given to any type of system design to improve the reliability of wastewater stabilization pond systems to remove the nitrogen (N) and phosphorus (P) in wastewater. However, as more stringent nutrient standards are adopted, nutrient removal processes must now be included in designs for new systems and added to existing systems. Nitrogen removal can be critical in many situations, as ammonia (NH₃), even at low concentrations, can adversely affect aquatic life in receiving waters, and the addition of nitrate (NO₃⁻) to surface waters is a major contributor to eutrophication. Nitrate is often the controlling parameter for the design of land treatment systems. Any nitrogen removal in the primary pond units can result in very significant savings in acreage required for final land treatment. Phosphorus, which is limiting for algal growth, is present at concentrations in municipal wastewater that stimulate that growth and those levels must be reduced to control eutrophication.

The dominant forms of nitrogen coming into a conventional facultative wastewater treatment pond system are referred to as the total Kjeldahl nitrogen (TKN), which is the sum of the organic nitrogen, NH_3 , and ammonium ions (NH_4^+). In biological systems, such as aerobic ponds, where the pH is usually less than 8, the majority of the NH_3 is the ionic form. TKN can be reduced through several processes, including gaseous NH_3 stripping to the atmosphere, NH_3 assimilation into the biomass, biological nitrification/denitrification, and sedimentation of insoluble organic nitrogen. These processes are affected by temperature, dissolved oxygen (DO) concentration, pH value, retention time, and wastewater characteristics. Within bottom sediments under anoxic conditions in facultative ponds, denitrification can take place. Temperature, redox potential, and sediment characteristics affect the rate of denitrification. In well-designed aerated ponds with good mixing conditions and distribution of DO, however, the effect on the rate of denitrification will be negligible. The capacity of conventional facultative and aerated ponds to convert NH_3 is discussed in the following sections. Several commercial processes that have been developed for nitrogen removal are also described. There is, however, little operational data available to demonstrate the effectiveness of the commercial units.

8.3 FACULTATIVE PONDS

Nitrogen loss from streams, lakes, impoundments, and wastewater ponds has been observed for many years. Data on nitrogen losses in pond systems were not sufficient to conduct a comprehensive analysis until the early 1980s, and even then there was no agreement as to the mechanisms of removal. Investigators have suggested algal uptake, sludge deposition, adsorption by bottom soils, nitrification, denitrification, and loss of NH_3 as a gas to the atmosphere (volatilization). A combination of factors may be responsible (Pano and Middlebrooks, 1982; Reed, 1984; Reed et al., 1995). The dominant mechanism, under favorable conditions, is thought to be loss by volatilization to the atmosphere. The several mechanisms are depicted in Figure 8.1.

8.3.1 PERFORMANCE

The U.S. Environmental Protection Agency (USEPA) undertook a number of studies of facultative wastewater pond systems in the late 1970s (Bowen, 1977; Hill and Shindala, 1977; McKinney, 1977; Reynolds et al., 1977). The results verified the hypothesis that significant nitrogen removal occurs in pond systems. The findings from those studies are summarized in Table 8.3. Nitrogen removal is related to pH, detention time, and temperature. Fluctuations in pH resulting from the interaction of algae and bicarbonate (HCO_3^-) change the alkalinity; thus, pH is an important parameter to monitor. Under ideal conditions, up to 90% NH_3 removal can be achieved in facultative wastewater treatment ponds.

Several studies on nitrogen removal have been completed more recently, but the quantity of data is still limited. A study of 178 facultative ponds in France showed an average nitrogen removal of 60 to 70% (Racault et al., 1995). An 82% reduction in NH_3 was observed in a study of four small-scale facultative ponds in series for 21

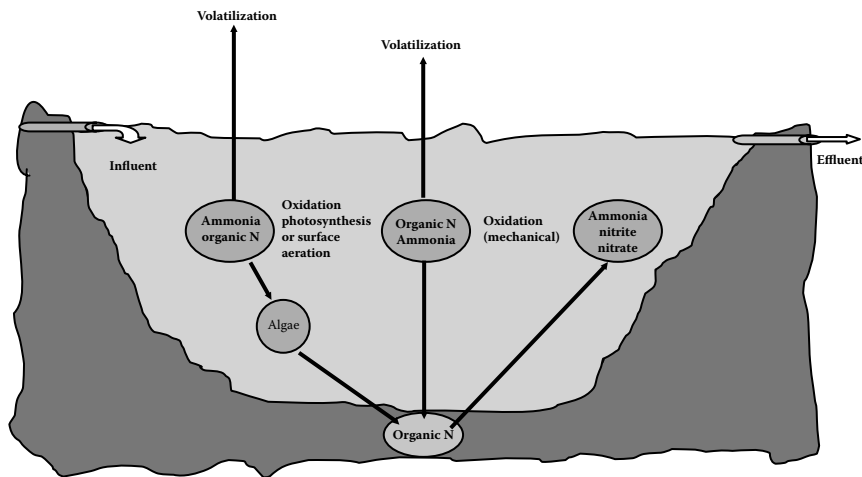


FIGURE 8.1 Generalized nitrogen pathways in wastewater ponds.

months (Wrigley and Toerien, 1990). Shilton (1995) quantified the removal of NH_3 from a facultative pond treating piggery wastewater and found that the rate of volatilization varied from 355 to 1534 $\text{mg/m}^2/\text{day}$ (0.07 to 0.314 $\text{lb}/1000 \text{ ft}^2/\text{day}$). The rate of volatilization increased at higher concentrations of NH_3 and TKN.

When Soares et al. (1996) monitored NH_3 removal in a wastewater treatment pond complex of different geometries and depths in Brazil, they found that the NH_3 concentrations were lowered to 5 mg/L in the maturation ponds so the effluent could be discharged to surface waters. The NH_3 removal in the facultative and maturation ponds could be modeled by the equations based on the volatilization mechanism proposed by Pano and Middlebrooks (1982).

Using ^{15}N -labeled NH_3 , Camargo Valero and Mara (2007) demonstrated the uptake of NH_3 by the algal biomass in a pond, followed by assimilation into the suspended organic fraction (85% in the effluent) and movement into the pond benthos by sedimentation. A study of ponds in Kansas (Tate et al., 2002) showed increased NH_3 in August, which would tend to confirm that it is taken up by algae, and its movement to the benthos, from which it is released under later summer conditions.

TABLE 8.3
Annual Values from USEPA Facultative Wastewater Pond Studies

Location	Hydraulic Retention Time (days)	Temperature (Average Range) ($^{\circ}\text{C}$)	pH (Median)	Alkalinity (mg/L)	Nitrogen Removal (%)
Peterborough (3 cells)	107	−7 to 20	7.1	85	43
Kilmichael (3 cells)	214	4.5 to 26	8.2	116	80
Eudora (3 cells)	231	1.1 to 27	8.4	284	82
Corinne (first 3 cells)	42	−3.9 to 23	9.4	555	46

8.3.2 THEORETICAL CONSIDERATIONS

It is hypothesized that NH_3 removal in facultative wastewater treatment ponds occurs via three mechanisms: gaseous NH_3 stripping to the atmosphere, NH_3 assimilation in algal biomass, and biological nitrification. The low concentrations of NO_3^- and NO_2^- measured in pond effluents indicate that nitrification generally does not account for a significant portion of NH_3 removal. Ammonia assimilation in algal biomass depends on the biological activity in the system and is affected by temperature, organic load, detention time, and wastewater characteristics. The rate of gaseous NH_3 losses to the atmosphere depends mainly on the pH value, temperature, and mixing conditions in the pond. Alkaline pH shifts the equilibrium equation $\text{NH}_3\uparrow + \text{H}_2\text{O} \leftrightarrow \text{NH}_4^+ + \text{OH}^-$ toward gaseous NH_3 , whereas the mixing conditions affect the magnitude of the mass transfer coefficient. Temperature affects both the equilibrium constant and mass transfer coefficient.

At low temperatures, when biological activity decreases and the pond contents are generally well mixed due to wind effects, stripping will be the major process for NH_3 removal in facultative wastewater treatment ponds. The NH_3 stripping process in ponds may be expressed by assuming a first-order reaction (Stratton, 1968, 1969), and the mass balance equation will be

$$VdC/dt = Q(C_o - C_e) - kA(\text{NH}_3) \quad (8.1)$$

where

V = Volume of the pond (m^3).

C = Average pond contents concentration of $(\text{NH}_4^+ + \text{NH}_3)$ (mg/L as N).

t = Time (days).

Q = Flow rate (m^3/day).

C_o = Influent concentration of $(\text{NH}_4^+ + \text{NH}_3)$ (mg/L as N).

C_e = Effluent concentration of $(\text{NH}_4^+ + \text{NH}_3)$ (mg/L as N).

k = Mass transfer coefficient (m/day).

A = Surface area of the pond (m^2).

The equilibrium equation for NH_3 dissociation may be expressed as

$$K_b = \frac{[\text{NH}_4^+][\text{OH}^-]}{[\text{NH}_3]} \quad (8.2)$$

where K_b is the NH_3 dissociation constant.

By modifying Equation 8.2, the gaseous NH_3 concentration may be expressed as a function of the pH value and total NH_3 concentration $(\text{NH}_4^+ + \text{NH}_3)$ as follows:

$$[\text{H}^+] = \frac{K_w}{[\text{OH}^-]} \quad (8.3)$$

$$C = \text{NH}_4^+ + \text{NH}_3 \quad (8.4)$$

$$\text{NH}_3 + \frac{C}{1 + 10^{pK_w - pK_b - \text{pH}}} \quad (8.5)$$

where

$$pK_w = -\log K_w$$

$$pK_b = -\log K_b$$

Assuming steady-state conditions and a completely mixed pond where $C_e = C$, Equations 8.4 and 8.5 will yield the following relationship:

$$\frac{C_e}{C_o} = \frac{1}{1 + \frac{A}{Q} K \left[\frac{1}{1 + 10^{pK_w - pK_b - \text{pH}}} \right]} \quad (8.6)$$

This relationship emphasizes the effect of pH, temperature (pK_w and pK_b are functions of temperature), and hydraulic loading rate on NH_3 removal.

Experiments on NH_3 stripping conducted by Stratton (1968, 1969) showed that the NH_3 loss-rate constant was dependent on the pH value and temperature ($T = ^\circ\text{C}$) as shown in the following relationships:

$$\text{NH}_3 \text{ loss rate constant} \propto e^{1.57(\text{pH}-8.5)} \quad (8.7)$$

$$\text{NH}_3 \text{ loss rate constant} \propto e^{0.13(T-20)} \quad (8.8)$$

King (1978) reported that only 4% nitrogen removal was achieved by harvesting floating *Cladophora fracta* from the first pond in a series of four receiving secondary effluents. The major nitrogen removal in the ponds was attributable to NH_3 gas stripping. The removal of total nitrogen was described by first-order kinetics using a plug flow model: $N_t = N_0 e^{-0.03t}$, where N_t = total nitrogen concentration (mg/L), N_0 = initial total nitrogen concentration (mg/L), and t = time (days).

During windy seasons or large-scale facultative steady-state conditions, well-designed ponds approach completely mixed conditions. Moreover, when NH_3 removal through biological activity becomes significant or NH_3 is released from anaerobic activity at the bottom of the pond, the expressions for NH_3 removal in the system must include these factors along with the theoretical consideration of NH_3 stripping. A mathematical relationship for total nitrogen removal based on the performance of three full-scale facultative wastewater treatment ponds is developed here that considers the theoretical approach and incorporates temperature, pH value, and hydraulic loading rate as variables. In this case, Equation 8.9 for TKN removal in facultative ponds is substituted for the theoretical expression for NH_3 stripping:

$$\frac{C_e}{C_o} = \frac{1}{1 + \frac{AK}{Q} \times f(\text{pH})} \quad (8.9)$$

where K is the removal rate coefficient (L/t), and $f(\text{pH})$ is a function of pH.

The K values are considered to be a function of temperature and mixing conditions. For a similar pond configuration and climatic region, the K values may be expressed as a function of temperature only. The function of pH, which is considered to be dependent on temperature, affects the pK_w and pK_b values, as well as the biological activity. Based on a statistical analysis of the data when incorporated into the equation, the pH function was found to describe an exponential relationship. As many reaction rate and temperature relationships are described by exponential functions, such as the van't Hoff–Arrhenius equation, it is not unreasonable to assume that such a relationship would apply to the application of the theoretical equation to a practical problem.

8.3.3 DESIGN MODELS

Data were collected on a frequent schedule for every cell in the pond system shown in Table 8.1 for at least a full annual cycle. A quantitative analysis of all major variables was performed and several design models were developed. Both plug flow and complete mixing models were useful in predicting nitrogen removal in facultative pond systems (see sections that follow). They are first-order models that depend on pH, temperature, and hydraulic retention time (HRT). They have been validated using data from other sources. Further validation of the models can be found in Crites et al. (2006), Reed (1984, 1985), and Reed et al. (1995). Both models assume that volatilization of NH_3 is the major pathway of nitrogen removal from wastewater treatment ponds. The models presented below are expressed in terms of total nitrogen and should not be confused with the equations reported by Pano and Middlebrooks (1982), which are limited to the NH_3 fraction (USEPA, 2011).

8.3.3.1 Model 1: Nitrogen Removal in Facultative Ponds—Plug Flow Model

This model is based on Reed (1985).

$$N_e = N_0 e^{-k_T[t+60.6(\text{pH}-6.6)]} \quad (8.10)$$

where

N_e = Effluent total nitrogen (mg/L).

N_0 = Influent total nitrogen (mg/L).

k_T = Temperature-dependent rate constant = $k_{20}(\theta)^{(T-20)}$, where k_{20} = rate constant at 20°C and $\theta = 1.039$.

t = Detention time in system (days).

pH = pH of near-surface bulk liquid.

See Reed (1984) for typical pH values or estimate with $\text{pH} = 7.3e^{0.0005\text{ALK}}$, where ALK is the expected influent alkalinity (mg/L), derived from data in USEPA (1983) and Reed (1984).

Use the Mancini and Barnhart (1976) equation for pond water temperature determination:

$$T = \frac{0.5AT_a + QT_i}{0.5A + Q} \quad (8.11)$$

where

A = Surface area of pond (m^2).

T_a = Ambient air temperature ($^{\circ}\text{C}$).

T_i = Influent temperature ($^{\circ}\text{C}$).

Q = Influent flow rate (m^3/day).

A high rate of NH_3 removal by air stripping in advanced wastewater treatment depends on a high (>10) chemically adjusted pH. The algae-carbonate interactions in wastewater ponds can elevate the pH to similar levels for brief periods during the day. At other times, at lower pH levels, the rate of removal may be slower, but the long detention time results in lower nitrogen concentrations in the effluent.

8.3.3.2 Model 2: Nitrogen Removal in Facultative Ponds—Complete Mix Model

This model is based on Middlebrooks (1985).

$$N_e = \frac{N_0}{1 + t(0.000576T - 0.00028)e^{(1.080 - 0.042T)(\text{pH} - 6.6)}}$$

where

N_e = Effluent total nitrogen (mg/L).

N_0 = Influent total nitrogen (mg/L).

t = Detention time (days).

T = Temperature of pond water ($^{\circ}\text{C}$).

pH = pH of near-surface bulk liquid.

Use the Mancini and Barnhart (1976) equation to determine the pond water temperature.

These models have been used in the design of several pond systems and have been found to work as predicted. It is nevertheless likely that other removal mechanisms are at work (Camargo Valero and Mara, 2007); therefore, these models should be used only as a first step in designing for NH_3 removal in ponds.

8.3.4 APPLICABILITY, LIMITATIONS, AND OPERATION AND MAINTENANCE

Nitrogen removal occurs in facultative wastewater treatment ponds and may be reasonably predicted for design purposes with either of the two models. Nitrogen removal in ponds may be more cost effective than other alternatives for removal or NH_3 conversion. These models should be useful for new or existing wastewater ponds when nitrogen removal or NH_3 conversion is required. The design of new

systems would typically base detention time on the biochemical oxygen demand (BOD₅) removal requirements. The nitrogen removal that will occur during that time can then be calculated with either model. It is prudent to assume that the remaining nitrogen in the effluent will be NH₃ and to design any further removal or conversion for that amount. A final step would be to compare the cost of additional detention time in an expanded pond system for nitrogen removal with other removal alternatives. Use of these models is particularly important when ponds are used as a component in land treatment systems, as total nitrogen is often the controlling design parameter. A reduction in pond effluent nitrogen will often permit a significant reduction in the area needed for land treatment. Other than the requirement for sufficient pond acreage, the facultative pond system can be expected to provide maximum NH₃ conversion during the summer months, occasionally exceeding 90%. This level of treatment cannot be expected during winter months. Operation and maintenance are the same as for facultative ponds designed to remove BOD₅.

8.4 AERATED PONDS

The same conditions that apply to push the equilibrium of NH₄⁺ to NH₃ in conventional facultative pond systems also apply to aerobic ponds. The USEPA sponsored comprehensive studies of aerated pond systems between 1978 and 1980 that provided information about nitrogen removal (see Tables 8.4 and 8.5; also see Case Studies 8.1 and 8.2 for background on two of the systems). The results verify the consensus of previous investigators that nitrogen removal is related to pH, detention time, and temperature in the pond system.

TABLE 8.4
Wastewater Characteristics and Operating Conditions for Five Aerated Ponds

Parameter	Pawnee, Illinois	Bixby, Oklahoma	Koshkonong, Wisconsin	Windber, Pennsylvania	North Gulfport, Mississippi
BOD (mg/L)	473	368	85	173	178
COD (mg/L)	1026	635	196	424	338
TKN (mg/L)	51.41	45.04	15.3	24.33	26.5
NH ₃ -N (g/L)	26.32	29.58	10.04	22.85	15.7
Alkalinity(mg/L)	242	154	397	67	144
pH	6.8–7.4	6.1–7.1	7.2–7.4	5.6–6.9	6.7–7.5
Hydraulic loading rate (MGD)	0.0213	0.0285	0.0423	0.0663	0.0873
Organic loading rate (kg BOD ₅ /ha/day)	151	161	87	285	486
Detention time (days)	143	107	72	46	22

Source: USEPA, *Biological Nutrient Removal Processes and Costs*, U.S. Environmental Protection Agency, Washington, DC, 2007 (data from Earnest et al., 1978; Englande, 1980; Gurnham et al., 1979; Polkowski, 1979; Reid and Streebin, 1979; Russell et al., 1980).

TABLE 8.5
Nitrogen Removal in Aerated Ponds

Parameter	Location					
	Pawnee, Illinois		Bixby, Oklahoma		Koshkonong, Wisconsin	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
TKN (mg/L)	51.4	5.0	45.0	8.4	15.3	7.6
NH ₃ (mg/L)	26.3	1.3	29.6	3.5	10.0	5.3
NO ₃ ⁻ (mg/L)	—	0.8	—	—	1.7	4.4
NO ₂ ⁻ (mg/L)	0.1	—	—	0.1	—	—
Alkalinity (mg/L)	242	161	154	70	397	382
pH	6.8–7.4	7.8–9.3	6.1–7.1	6.7–9.2	7.2–7.4	7.4–7.9
Temperature (°C)	—	11.3	—	16.3	—	11.6
Dissolved oxygen (mg/L)	—	1.9–16.0	—	3.9–13.5	—	7.6–15.3
	Windber, Pennsylvania		North Gulfport, Mississippi		Mt. Shasta, California	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
TKN (mg/L)	24.3	23.6	26.5	10.8	15.7	11.1
NH ₃ (mg/L)	22.9	22.9	15.7	5.1	10.3	5.4
NO ₃ ⁻ (mg/L)	—	0.7	—	2.4	0.3	0.7
NO ₂ ⁻ (mg/L)	—	0.2	—	0.6	0.2	0.5
Alkalinity (mg/L)	67	82	144	102	93	74
pH	5.6–6.9	6.8–85	6.7–7.5	6.8–7.5	6.5–7.6	7.4–9.7
Temp (°C)	—	13.9	—	21.5	—	13.7
Dissolved oxygen (mg/L)	—	5.7–15.0	—	0.8–9.3	—	10.9–14.0
Source: Adapted from USEPA, <i>Design Manual: Municipal Wastewater Stabilization Ponds</i> , EPA 625/1-81-015, U.S. Environmental Protection Agency, Cincinnati, OH, 1983.						

Case Study 8.1. Orange Grove Aerated Lagoon*

The Orange Grove Aerobic Lagoon is located in Harrison County, Mississippi, approximately eight miles north of Gulfport. The municipal treatment system services a community consisting of residential homes, shopping centers, etc. with a population of approximately 5000. The continuous-flow lagoons have been in operation for approximately 12 years. The system was originally designed as multi-celled stabilization lagoons operated in series. Eight years previously the first cell had been upgraded to an aerated lagoon, but then a change in operation

* Adapted from Englande, Jr., A.J., *Performance Evaluation of the Aerated Lagoon System at North Gulfport, Mississippi*, EPA 600/2-80-006, U.S. Environmental Protection Agency, Cincinnati, OH, 1980.

1. Cell A1. Aerated Facultative Lagoon
 - a. *Size*: 63 m × 163 m (206 ft × 535 ft)
 - b. *Area*: 1.0 ha (2.5 ac)
 - c. *Depth*: 1.9 m (6.3 ft)
 - d. *Volume*: 19,682 m³ (5.2 MG)
 - e. *Flow*: 1892 m³/day (500,000 GPD) (design)
 - f. *Detention time*: 10 days (design)
 - g. *Hydraulic loading*: 185 mm/day (7.3 in./day) (design)
 - h. *Organic loading*: 374 kg/ha/day (334 lb BOD₅/ac/day) (design)
 - i. *Flow pattern*: Plug flow
 - j. *Aeration equipment*: 8 Welles surface aerators, 3.73 kw (5 hp)/aerator
 - k. *Power level*: 1.5×10^{-3} kw/m³ (7.7 hp/MG)
 - l. *Dikes*: Unlined with 3:1 slopes
 - m. *Flow measurement*: Martig BHB 1 unit with a 38-cm (15-in.) sensing ring calibrated to a Bristol G5000 recorder
 - n. *Inlet*: Two 25-cm (10-in.) diameter cast iron pipes (parallel, 0.61 m) extending 10.7 m (35 ft) into the lagoon (above water)
2. Cell A2. Aerated Facultative Lagoon
 - a. *Size*: 124 m × 126 m (407 ft × 412 ft)
 - b. *Area*: 1.5 ha (3.8 ac)
 - c. *Depth*: 1.9 m (6.3 ft)
 - d. *Volume*: 29,902 m³ (7.9 MG)
 - e. *Flow*: 1892 m³/day (500,000 GPD) (design)
 - f. *Detention time*: 15.8 days (design)
 - g. *Hydraulic loading*: 121 mm/day (4.8 in./day) (design)
 - h. *Organic loading*: 86 kg/ha/day (77 lb BOD₅/ac/day) (design)
 - i. *Flow pattern*: Plug flow
 - j. *Aeration equipment*: 9 Welles surface aerators, 5.59 kw (7.5 hp)/aerator
 - k. *Power level*: 1.67×10^{-3} kw/m³ (8.5 hp/MG)
3. Chlorination
 - a. Chlorinated prior to discharge into settling Cell S2
 - b. Chlorinating equipment: auto switchover type 45 kg/day · m (100 lb/day · m)
4. Cell S2. Settling Basin
 - a. *Size*: 29 m × 63 m (95 ft × 205 ft)
 - b. *Area*: 1809 m² (19,475 ft²)
 - c. *Depth*: 1.8 m (6.0 ft)
 - d. *Volume*: 3293 m³ (0.87 MG)
 - e. *Flow*: 1324 m³/day (350,000 GPD) (design)
 - f. *Detention time*: 2.5 days (design)
 - g. *Dikes*: Unlined with 3:1 slopes

Overall system performance (see Figure CS 8.1.1) was based on the quality of effluent from Cell S2; hence, Cells S1, S3, and S4 were not included in the study evaluation.

Case Study 8.2. Three-Lagoon Wastewater Treatment at Pawnee, Illinois*

Pawnee, Illinois, is located approximately 15 miles (24 km) south of Springfield, the state capital. The climate in the central part of the state is continental, with warm summers and cold winters. The state lies within the principal storm tracks that cross the country and as a consequence experiences marked weather changes, especially in winter. Mean average temperature for the area is 51°F (10°C), ranging from a January mean average of 26°F (−1°C) to 75°F (24°C) in July. Average daily minimum temperatures range from 18°F (−8°C) to 64°F (18°C); average daily maximum temperatures range from 34°F (1°C) to 85°F (30°C). Total precipitation averages 36 in. (914 mm); the snowfall average is 22 in. (559 mm). The period of heaviest precipitation occurs between March and September. Prevailing winds are from the south, and average 7 mph (11 km/hr) with gusts to 70 mph (110 km/hr).

The Village of Pawnee Trustees issued \$800,000 of revenue bonds to build a modern sewage collection system. The money raised was used to construct 83,000 linear feet of sewers, four lift stations, and an Air-Aqua tertiary lagoon wastewater treatment system. The population of Pawnee at the time was approximately 2000, with about 90% connected to the sewer system. The wastewater treatment plant is located north of the village center and discharges to Horse Creek, a tributary of the south fork of the Sangamon River, in the Illinois river system.

A lagoon system such as the one installed at Pawnee is estimated to cost one-quarter as much as a comparable activated sludge waste treatment plant, and operation costs are also reported to be lower (Michel, 1970; Smith and Eilers, 1970). Another advantage to a lagoon system for a small community is that there is no need for solids handling equipment, which adds to the cost of a secondary treatment plant.

The wastewater treatment plant (see Figure CS8.2.1) has a design capacity of 1893 m³/day (0.5 MGD) to accommodate domestic waste generated by a population of 5000, with a BOD₅ design loading of 386 kg/day (850 lb/day) at an average of 200 mg BOD₅/L influent. It includes three lagoons, in series, each equipped with an Air-Aqua aeration system (Hinde Engineering Company), followed by sand filters and chlorination. The Air-Aqua system provides diffuser air aeration from special tubes laid on the bottom of the lagoons. The transverse layout of the aeration tubes was reported to provide convenient and efficient air flow from headers. The layout was also claimed to compartmentalize flow, which is divided by air-bubble curtains. It was further claimed that such a layout minimizes short-circuiting, extends the aeration time, and provides aeration of the entire lagoon volume. Spacing of the tubes is designed to provide aeration approximately in proportion to the demand.

* Adapted from Gurnham, C.R., et al., *Performance Evaluation of the Existing Three-Lagoon Wastewater Treatment Plant at Pawnee, Illinois*, EPA 600/2-79-043, U.S. Environmental Protection Agency, Cincinnati, OH, 1979.

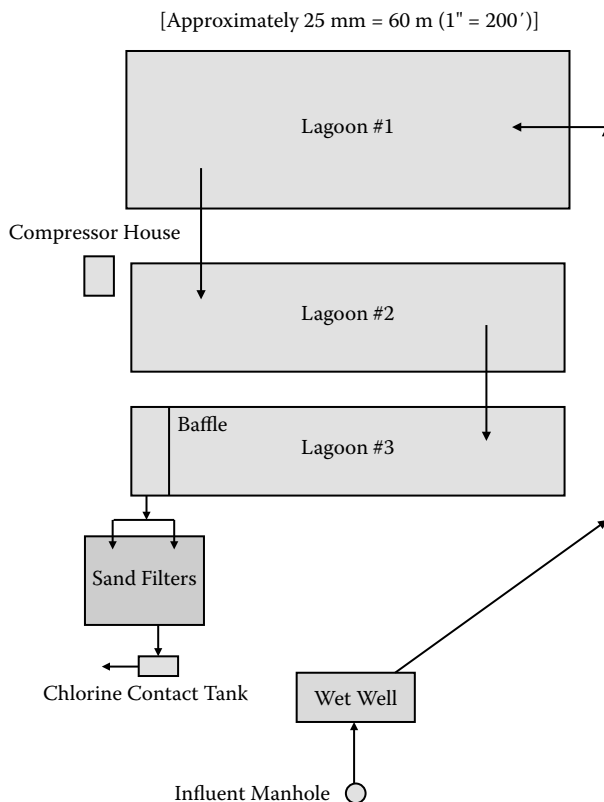


FIGURE CS8.2.1 Pawnee sewage treatment plant.

Lagoon 1 is 110×226 m (360×740 ft) to yield a rectangular surface area of 2.47 ha (6.1 ac). The lagoon is 3 m (10 ft) deep with 3-to-1 sloping sides. The capacity of the lagoon is $66,700 \text{ m}^3$ (17.6 million gallons). It contains 58 lines of aeration tubing spaced 3 m (10 ft) apart at the inlet end of the lagoon and 6 m (20 ft) apart toward the outflow end. These measurements and figures correspond to a design loading on the primary lagoon of $157 \text{ kg BOD}_5/\text{ha}/\text{day}$ ($140 \text{ lb BOD}_5/\text{ac}/\text{day}$) and a design detention time of 35 days.

Lagoon 2 is 56×226 m (185×740 ft) to yield a surface area of 1.25 ha (3.1 ac). The lagoon is 3 m (10 ft) deep and has a capacity of $31,000 \text{ m}^3$ (8.2 million gallons). There are 36 lines of aeration tubing evenly spaced 6 m (20 ft) apart.

Lagoon 3 is 37×195 m (120×640 ft) to yield a surface area of 0.73 ha (1.8 ac). The lagoon is 3 m (10 ft) deep and has a capacity of $15,900 \text{ m}^3$ (4.2 million gallons). The lagoon has 32 lines of aeration tubing evenly spaced 6 m (20 ft) apart. There is an additional 30 m (100 ft) of length at the discharge end of this lagoon that is separated from the main section of the lagoon by a baffle and which provides a non-aerated chamber.

For the three lagoons, with a total of 4.45 ha (11 ac) of surface area, the design loading is 86 kg BOD₅/ha/day (77 lb BOD₅/ac/day). The design detention time, based on a total lagoon volume of 113,500 m³ (30 million gal), is 60 days.

During the first three months of the performance study, effluent flowed by gravity from the aerated lagoon system to two dosing tanks. From the tanks it was pumped alternately to two parallel banks of intermittent sand filters. Each bank contains four cells, operated in parallel, with any one or more capable of being taken out of service. The sand filters were subject to severe blockage problems. The filters were removed from service in June, as they did not serve the purposes they were intended for. Filtered effluent discharges to a chlorine contact chamber, where a 12.5% sodium hypochlorite solution is metered into the wastewater. Chlorine dosage is gauged to deliver 4 mg active chlorine per liter of wastewater. This dosage normally leaves slight chlorine residual in the treated effluent. Final effluent discharges to the creek.

8.4.1 EMPIRICAL DESIGN EQUATIONS

Table 8.6 contains a summary of selected equations developed to predict NH₃ and TKN removal in diffused air aerated ponds (Middlebrooks and Pano, 1983). All of the equations draw values from the same database. Different combinations of data were chosen and combined to develop several of the equations. The “System” column in Table 8.6 indicates which ponds or series of ponds were used to develop each equation. These data were analyzed statistically and the equations were selected based on the best statistical fit for the various combinations. It should be noted that the combinations of datasets are not directly comparable.

An examination of the HRT calculated using the various formulas for TKN removal show that the greatest difference between the maximum and minimum detention times calculated from the equation is 14%. In view of the variation in methods used, this variability is reasonable. All of the relationships are statistically significant at levels higher than 1%. As a result, any of them may be applied to estimate TKN removal in an aerated pond design. Given the simplicity of the plug flow model and the fraction-removed model, it is recommended that one or both be used along with the theoretical models to verify that there will be adequate removal in the event that unusual BOD₅ loading rates are encountered. Using any of these expressions will result in an estimate of TKN removal that is likely to occur in diffused-air aerated ponds. Unfortunately, data are not available to develop similar relationships for surface aerated ponds.

Although the relationships developed to predict NH₃ removal are significant for all of the equations presented in Table 8.6, the agreement between the calculated HRT for NH₃ removal differed significantly from that observed for the TKN data. This is not surprising in view of the variety of mechanisms involved in NH₃ production and removal in wastewater ponds, but it does complicate the use of the equations to estimate NH₃ removal in aerated ponds. Statistically, any of the expressions may be used to calculate the HRT required to achieve a certain percent reduction in NH₃.

TABLE 8.6**Comparisons of Various Equations to Predict NH_3 and TKN Removal in Diffused-Air Aerated Ponds**

Equation Used to Estimate Hydraulic Retention Time or Effluent Concentration	Correlation Coefficient	Hydraulic Retention Time (days)	Compared with Maximum Retention Time (% Difference)	System (Mean Monthly Data)
TKN removal				
$\ln C_e/C_o = 0.0129(\text{Detention time})$	0.911	125	5.3	Ponds 1, 2, 3
TKN removal rate				
$\text{TKN}_{rr} = 0.0809(\text{TKN loading rate})$	0.983	132	9	Total system
TKN removal rate				
$\text{TKN}_{rr} = 0.0946(\text{BOD}_5 \text{ loading rate})$	0.967	113	14.4	Total system
TKN fraction removed				
$\text{TKN}_{fr} = 0.0062(\text{Detention time})$	0.959	129	2.3	Ponds 1, 2, 3
NH_3 removal				
$\ln C_e/C_o = -0.0205(\text{Detention time})$	0.798	79	40.2	All data
NH_3 removal rate				
$\text{NH}_{3rr} = 0.869(\text{NH}_3\text{-N loading rate})$	0.968	92	30.3	Total system
NH_3 removal rate				
$\text{NH}_{3rr} = 0.0606(\text{BOD}_5 \text{ loading rate})$	0.932	132	0	Total system
NH_3 fraction removed				
$\text{NH}_{3fr} = 0.0066(\text{Detention time})$	0.936	121	8.3	Ponds 1, 2, 3

Source: USEPA, *Biological Nutrient Removal Processes and Costs*, U.S. Environmental Protection Agency, Washington, DC, 2007 (based on Middlebrooks and Pano, 1983).

Perhaps the best equation to use when designing for NH_3 removal is the relationship between the fraction removed and the HRT. The correlation coefficient for this relationship is higher than the correlation coefficient for the plug flow model, and both equations are relatively straightforward to use (USEPA, 2011).

8.4.2 NITROGEN REMOVAL IN CONTINUOUS FEED INTERNATIONAL DISCHARGE BASINS

Continuous feed intermittent discharge (CFID) basins can be used in aerated pond systems for nitrification and denitrification (Rich, 1996, 1999). The systems are designed to use in-basin sedimentation to uncouple the solids retention time from the HRT. The influent flow is continuous. A single basin has a dividing baffle to prevent short-circuiting. Some CFID systems have experienced major operational problems with short-circuiting and sludge bulking; however, by minimizing these problems with design changes the systems can be made to function properly. CFID design modifications can be made to overcome most difficulties, and details are presented in Rich (1999).

DID YOU KNOW?

Sludge bulking occurs when the sludge fails to separate out in the sedimentation (settling) tanks. The main cause of sludge bulking is the growth of filamentous bacteria. To avoid sludge bulking, some of the flow that enters the reactor can be bypassed, the recycle ratio can be increased, lime or soda can be added to the reactor, or the reaeration rate can be increased.

8.4.2.1 Advantages and Disadvantages

When designed and built correctly, the system is capable of producing an effluent in a pond system comparable to activated sludge systems designed for nitrification/denitrification. Experience with the system, however, is limited.

8.4.2.2 Design Criteria

The basic CFID system consists of a single reactor basin divided into two cells with a floating baffle. The two cells are referred to as the influent cell (Cell 1) and the effluent cell (Cell 2). Mixed liquor is recycled from Cell 2 to the headworks to provide a high ratio of soluble biodegradable organics to organisms and the O_2 source is primarily NO_3^- . This approach is used to control bulking. Although some nitrification will occur in the influent cell, the system is designed for nitrification to occur in the effluent cell. For further details of the operation of the CFID systems, see Rich (1999).

8.4.2.3 Limitations, Operations, Maintenance, and Costs

There is little proven design information, and operation difficulties have been encountered. It is expected that maintenance would be the same as that required for other aerobic ponds. Construction costs would be the same as those for conventional aerobic pond systems. Considerable saving should accrue when comparing the cost to produce an effluent quality with a CFID system with an equivalent effluent produced by an activated sludge system designed for nitrification/denitrification.

8.4.2.4 General Applicability

This method is a design for nitrification in an aerobic pond (Rich, 1999). The equations in Table 8.6 are empirical and may or may not apply to a general design. That said, they show what might be expected in terms of nitrogen removal. Designing a pond system to nitrify wastewater is not difficult if the water temperature and detention time are adequate to support nitrifiers and sufficient DO is supplied. Recycling of the mixed liquor is a significant benefit. As with all treatment methods, an economic analysis should be performed to determine whether this system is cost effective.

8.4.3 NITRIFICATION USING FIXED FILM MEDIA

In addition to the proprietary systems described later in this chapter, other studies have been conducted using baffles and suspended materials as media for attached growth of nitrifying organism (Polprasert and Agarwalla, 1995; Reynolds et al., 1975; Ripple, 2002). Nitrification is a function of temperature, and where temperature was

a factor in the studies there was a significant decline in nitrification. It is not clear that the impact of winter temperatures can be overcome when the water temperature drops below 10°C.

8.4.4 PUMP SYSTEMS, INC. BATCH STUDY

A solar-powered circulator (equivalent to the Solar Bee Model SB2500) was installed in an 11.7-ha pond with a depth of 4.5 m at Dickson, North Dakota, with no incoming wastewater. The circulator flow rate was 9463 L (2500 gal) per minute. The NH_3 concentration at the beginning of the experiment was approximately 20 mg/L. Dissolved oxygen, pH, BOD_5 , TSS, NH_3 , water temperature, and other parameters were measured over a 90-day period at various locations and depths. Over 1500 samples were collected over the test period. Average data for the various locations and depths are shown in Table 8.7. The average water temperature was 20.5°C. DO was present throughout the pond at all depths but on occasion dropped to 0.4 mg/L at the bottom. These occasional low DO concentrations may have had an adverse effect on the results presented below, but they do provide some guidance as to how to estimate the expected conversion of NH_3 in a partial mix aerobic pond system (see Equation 8.9).

TABLE 8.7
Average Values for Batch Test in
Pond 4 at Dickinson, North Dakota

Days	$\ln C_e/C_o$	pH
0	0	7.7
1	0.15	7.7
7	0.21	7.7
12	0.16	8.0
13	0.11	8.1
19	-0.06	8.4
26	-0.36	8.8
29	-0.36	8.7
36	-0.60	8.8
42	-0.67	8.6
48	-0.79	8.5
50	-0.82	8.5
57	-0.76	7.7
62	-0.75	8.0
70	-0.48	8.1
76	-0.62	8.0
84	-0.74	7.8
90	-0.91	8.1

Note: Area = 11.7 ha (29 ac); no inflow. C_o = influent concentration of (NH_4^+ + NH_3) (mg/L) as N. C_e = effluent concentration of (NH_4^+ + NH_3) (mg/L) as N.

The reduction in NH_4^+ with time was directly related to the variation in pH value (Table 8.7). When the pH exceeded 8.0, the reduction in NH_4^+ increased, implying a greater loss of the NH_3 to the atmosphere. The results of this experiment show the low reaction rate for nitrification that occurs in partial mix aerobic ponds. The reaction rate of 0.0107/day obtained at an average temperature of 20.5°C in the Dickinson experiments agrees with results obtained with data collected in an aerobic pond located in Wisconsin (Middlebrooks et al., 1982). At 1°C, the NH_3 conversion reaction rate for the Wisconsin partial mix pond ranged between 0.0035 and 0.0070 per day. Using the average value of 0.005 per day at 1°C and the value of 0.0107 per day obtained at Dickinson at 20.5°C, an approximate value of 1.04 can be inserted into the θ in the classic temperature correction equation: $k_T = k_{20}(1.04)^{(T-20)}$.

8.4.5 NITROGEN REMOVAL IN PONDS WITH WETLANDS AND GRAVEL NITRIFICATION FILTERS

The nitrification filter bed (NFB) was developed by Sherwood C. Reed (Reed et al., 1995; USEPA, 2011). The NFB has been installed at three locations in the United States. The system was developed as a retrofit for existing free water surface (FWS) and subsurface flow (SF) wetland systems having trouble meeting NH_3 effluent standards. Schematic diagrams of both FWS and SF wetlands fitted with NFBs are shown in Figure 8.2. The NFB is a vertical-flow gravel filter bed located on top of existing wetlands. When applied to the FWS wetland, the fine gravel bed is supported on a coarse gravel layer to ensure aerobic conditions in the NFB.

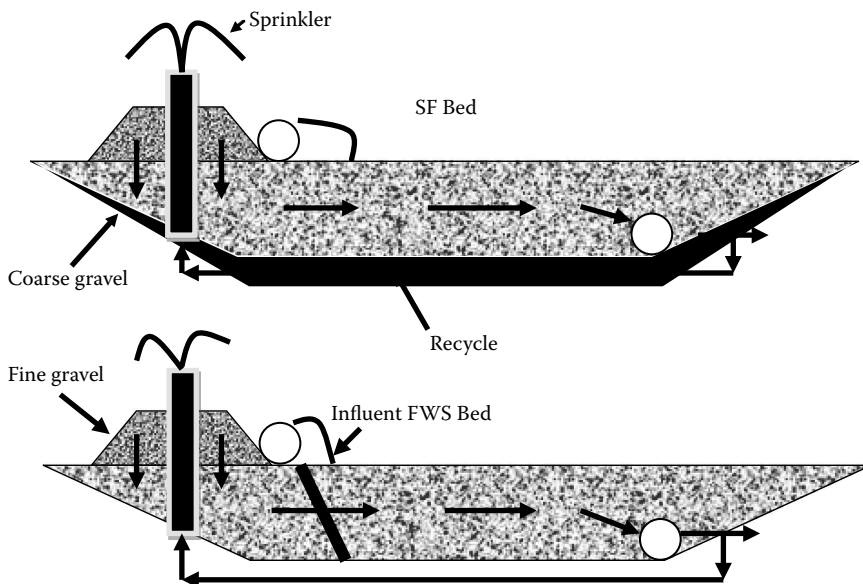


FIGURE 8.2 Diagram of nitrification filter bed. (Adapted from Reed, S.C., et al., *Natural Systems for Waste Management and Treatment*, 2nd ed., McGraw-Hill, New York, 1995.)

Nitrification filter bed units can be located at the front or near the end of the wetland where wetland effluent is pumped to the top of the NFB and distributed evenly over the surface. Introducing the wetland effluent to the NFB at the head of the system has the advantage of mixing the influent wastewater with the highly nitrified NFB effluent, which results in denitrification and removal of nitrogen from the system. In addition, the BOD_5 is reduced, and some of the alkalinity lost during nitrification will be recovered. If the NFB is placed at the end of the wetland, nitrification will occur, but denitrification will be limited and the NO_3^- will pass out of the system. This will require less pumping capacity, but the advantages of denitrification could easily offset the cost of pumping.

Although similar to a recirculation sand filter, the NFB uses gravel rather than sand and can process a much higher hydraulic loading rate than the sand filter. The hydraulic loading rate, including a 3:1 recycle ratio, for a NFB located in Kentucky is $4 \text{ m}^3/\text{m}^2/\text{day}$ ($100 \text{ gal}/\text{ft}^2/\text{day}$), in contrast to loadings on recirculating sand filters of $0.2 \text{ m}^3/\text{m}^2/\text{day}$ ($5 \text{ gal}/\text{ft}^2/\text{day}$).

Trickling filter and rotating biological contactor attached-growth concepts were used to develop a design relationship for the NFB; the relationship in Equation 8.12 was derived from curve-fitting performance data and should be used with caution. The equation should give reasonable estimates of the specific surface area to produce effluent NH_3 concentrations between 0 and 6 mg/L. Equation 8.12 has been verified at a 2-MGD system in Mandeville, Louisiana (Reed et al., 2003).

$$A_v = \frac{2713 - 1115(C_e) + 204(C_e)^2 - 12(C_e)^3}{k_T} \quad (8.12)$$

where

A_v = Specific surface area ($\text{m}^2/\text{kg } NH_3$ per day).

C_e = Desired NFB effluent NH_3 (mg/L).

k_T = Temperature-dependent coefficient.

$\theta(NH_3) = 1.048$; $\theta(NH_4^+) = 1.15$.

At temperatures $\geq 10^\circ\text{C}$, $k_T = (1)(1.048)^{(T-20)}$.

At temperatures 1 to 10°C , $k_T = (0.626)(1.15)^{(T-10)}$.

The following conditions are necessary for good nitrification performance:

- For BOD_5 , the TKN ratio must be less than one.
- Sufficient oxygen must be present.
- The surface must be moist at all times.
- Sufficient alkalinity must be available to support nitrification (approximately 10 g of alkalinity per g of NH_3).

The NFB bed depth ranges from 0.3 to 0.6 m, and the bed extends across the entire width of the wetland cell to ensure mixing with the influent wastewater (Figure 8.2). Sprinklers are used to distribute the wetland effluent over the surface of the NFB. In cold climates, it may be necessary to enclose the NFB to prevent freezing.

TABLE 8.8
Benton, Kentucky, Recirculating Gravel Filter/Constructed
Wetland Operational Data

Date	Carbonaceous BOD ₅ (mg/L)		Total Suspended Solids (mg/L)		NH ₃ (mg/L)
	Influent ^a	Effluent ^a	Influent ^a	Effluent ^a	Effluent ^a
April 1992	137 (3) ^b	4.2 (3)	89 (4)	4.5 (4)	1.5 (4)
May	180 (4)	2.6 (4)	273 (4)	2.8 (4)	2.0 (4)
June	160 (4)	4.6 (4)	124 (4)	7.0 (4)	1.5 (4)
July	208 (5)	6.7 (5)	113 (5)	13.8 (5)	1.9 (5)
August	202 (4)	4.0 (4)	144 (4)	4.5 (4)	1.3 (4)
September	270 (5)	4.9 (5)	164 (5)	5.6 (5)	1.4 (5)
October	153 (3)	5.7 (3)	131 (3)	2.7 (3)	0.7 (3)
November	99 (4)	18.0 (4)	195 (4)	9.0 (4)	0.5 (4)
December	216 (3)	54.5 (4)	124 (4)	2.5 (4)	0.9 (4)
January 1993	173 (4)	5.0 (4)	148 (4)	4.0 (4)	6.8 (4)
February	115 (4)	5.5 (4)	129 (4)	7.0 (4)	1.0 (4)
March	73 (5)	3.5 (5)	170 (5)	5.0 (5)	3.7 (5)
April	178 (4)	6.3 (4)	158 (4)	6.8 (4)	3.8 (4)
May	174 (5)	7.4 (5)	212 (5)	4.8 (5)	1.1 (5)

^a Numbers in parentheses are the number of samples.

^b BOD and TSS averages are from April 1992 to May 1993.

The Benton, Kentucky, NFB has been operating successfully at a hydraulic design flow of 3.79×10^6 L/day (1 MGD) with a wetland input of 20 mg/L NH₃ and an output of 2 mg/L. Performance data for approximately 3 years for the Benton facility are shown in Table 8.8.

When retrofitting an existing pond–wetland system for nitrification and nitrogen removal, the NFB appears to have economic advantages and simplicity of construction and operation. It also is likely that the NFB would be a viable alternative for nitrogen removal in the initial design of a pond–wetland system.

8.5 COMMERCIAL PRODUCTS

Numerous products and processes are offered as a means to improve pond performance and remove nitrogen. Several options are presented in the following sections (Burnett et al., 2004).

8.5.1 ADD SOLIDS RECYCLE

Adding solids recycle can be a reliable method of producing an effluent that can meet stringent NH₃ limits. With the addition of solids recycle, a pond is converted to a low mixed liquor suspended solids (MLSS) activated sludge system. This can

be accomplished using an external clarifier and adding a pump to return solids to the headworks. The BIOLAC® process uses an internal clarifier. Effluent from the clarifier is discharged to disinfection or routed through the subsequent cells of the pond system.

Successful operation of a low MLSS activated sludge system requires that the recycled solids be kept in suspension. The aerobic pond must be kept completely mixed. In most cases, a portion of the existing pond is partitioned into a complete-mix cell because the energy required to mix the cell is far greater than that required to reduce the BOD_5 or nitrify the NH_3 . The remaining portion of the system is used for polishing the effluent or storing the water before discharge.

Because the recycle system is an activated sludge variation, it can be designed and operated with traditional activated sludge design methods. Floating baffle curtains with exit ports are frequently used for cell partitioning. Excess sludge wasting can be accomplished in a separate holding pond, or downstream cells or the existing pond can be used to store and treat sludge for disposal.

A complete mix section can be located anywhere in the flow train of an aerobic pond system. If the complete mix cell is placed near the end of the flow train nitrification occurs after carbonaceous BOD_5 has been removed. With the complete mix zone first in the process, sludge can easily be returned to a manhole or other suitable location upstream of the plant influent. By recycling sludge to the headworks, anoxic conditions and a high food-to-microorganism ratio will help control sludge bulking, provide some denitrification, and recover alkalinity.

8.5.2 CONVERTING TO A SEQUENCING BATCH REACTOR OPERATION

Converting an aerobic pond to an activated sludge system can be accomplished by operating the aerobic pond as a sequencing batch reactor (SBR). A portion of the aerobic pond is partitioned into two or more complete mix SBR zones. SBRs operate in a sequence of fill, react, settle, and decant. In a single-train SBR, flow into the basin will continue through all four cycles. Where parallel systems exist, the SBR can be operated as a typical SBR system; however, the construction costs will be higher. Rich (1999) has referred to this operation as a CFID process, but it is the same as the commercial SBR system marketed by Austgen-Biojet. In SBR mode, aeration is used intermittently, and a decanting process transports the settled wastewater to downstream facultative cells or to a disinfection chamber before discharge. Decanting is accomplished with pumps, surface weirs, or floating decanting devices. A portion of the low MLSS must be wasted during the reaction (mixing and aeration) phase to keep the process in balance. Rich (1999) suggested adding a recycle pump station with mixed liquor returned to the influent sewer to provide an anoxic environment for control of sludge bulking.

8.5.3 INSTALL BIOMASS CARRIER ELEMENTS

The addition of baffles and suspended fabrics for attached growth to accumulate and reduce pollutants has been suggested for many years (Polprasert and Agarwalla, 1995; Reynolds et al., 1975). The availability of commercial fabrics for the removal

of NH_3 is a relatively new development. The carriers are plastic ribbons or wheels that are installed in the aerated zone to provide surface area for the growth of microorganisms. Provided that there is adequate surface area, nitrifying microorganisms can grow and multiply on the plastic surfaces and achieve NH_3 removal. The aerated cell does not have to be completely mixed, which is required in the recycle and SBR approaches, but the increased O_2 demand of the attached microorganisms must be met. Solids that drop from the biomass carriers settle or pass to the next pond cells. Sludge buildup will increase but will be reduced by anaerobic digestion, which will minimally affect the frequency at which sludge will have to be removed.

8.5.4 COMMERCIAL POND NITRIFICATION SYSTEMS

The following is a partial list of pond nitrification systems offered commercially:

1. ATLAS-IS™—Internal clarifier system by Environmental Dynamics, Inc.
2. CLEAR™ process—SBR variation by Environmental Dynamics, Inc.
3. Ashbrook SBR—SBR system by Ashbrook Corporation
4. AquaMat® process—Plastic biomass carrier ribbons by Nelson Environmental, Inc.
5. MBBR™ process—Plastic biomass carrier elements by Kaldness North America, Inc.
6. Poo-Gloo™—Substrate for bacteria by Wastewater Compliance Systems, Inc.

Experience with all of the systems listed above is limited, and it is difficult at this time to predict their applicability and performance. However, even with limited experience and although design criteria were not available, the SBR systems would be designed the same way as typical SBR. The quantities of plastic biomass required apparently are proprietary information. The design of the MBBR process is proprietary, as is the Poo-Gloo system. It is expected that the base costs associated with the type of pond into which the commercial equipment was placed would continue. Additional costs would include the commercial product and any associated operation and maintenance.

8.5.4.1 ATLAS-IS™

The Advanced Technology Pond Aeration System with Internal Separator (ATLAS-IS™) is offered by Environmental Dynamics, Inc. (EDI). It is designed to provide a high level of treatment with minimal operation and maintenance requirements. The process consists of a fine-bubble floating lateral aeration system that contains a series of internal clarifiers or settlers. The settlers are constructed of a plastic material and may contain lamellate baffles. The units are installed within a complete-mix zone of the aerated pond system. Mixed liquor enters the settling chamber through the bottom. A slight concentration of the low MLSS takes place in the settler as the mixed liquor rises and spills over a weir into an effluent pipe. No return activated sludge (RAS) or waste activated sludge (WAS) is required. Over

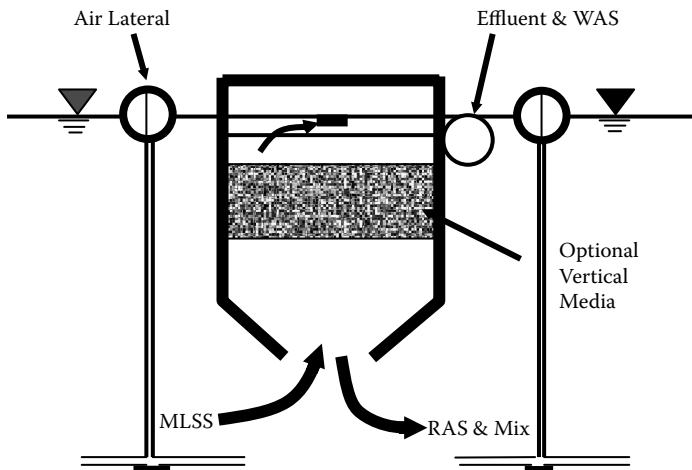


FIGURE 8.3 EDI ATLAS-IS™ internal pond settler. (From USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.)

time, the low MLSS will build up to a level adequate to grow nitrifying microorganisms. Some solids are carried downstream, so no separate sludge wasting is necessary. The ATLAS-IS system has been tested at Ashland, Missouri, and has been successful in building up low MLSS and in achieving nitrification. A diagram of the system is shown in Figure 8.3.

8.5.4.2 CLEAR™ Process

EDI also offers an SBR variant known as the Cyclical Pond Extended Aeration Reactor (CLEAR™). A completely mixed aerated pond cell is partitioned into three zones using floating baffle curtains. Influent is fed to each of the three zones in sequence. Aeration is applied to the zone receiving influent wastewater and, for part of this cycle, one of the other two zones. While the inflowing zone is aerated, the other two zones cycle between settling and decanting. WAS is removed using airlift pumps, either to downstream facultative ponds for storage or for further processing and disposal. A control system is provided to operate the motorized wastewater influent valves and decanters. There are currently no full-scale installations of the CLEAR process.

8.5.4.3 Ashbrook Sequencing Batch Reactor

The Ashbrook Corporation (Houston, Texas) SBR system consists of decanters, motorized valves, and a control system. A facility has been installed in a pond system in Quincy, Washington. The aerated pond was portioned into sections, and air was provided for complete mixing in two or more SBR cells. Operation is similar to a conventional SBR process, and the system in Quincy has been working well. Performance data are presented in Table 8.9.

TABLE 8.9
2002–2003 Average Influence/Effluent Data for Quincy, Washington, SBR System

	BOD (mg/L)	TSS (mg/L)	NH ₃ (mg/L)
Influent	145	159	19.0
Effluent	14	6	1.7

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

Note: Flow = 0.78 MGD.

8.5.4.4 AquaMat® Process Description

AquaMat® is a biomass carrier system marketed by Nelson Environmental, Inc. (Winnipeg, Manitoba). Plastic ribbons slightly more dense than water are connected to a plastic float; the ribbons extend into the wastestream 3 feet or more and provide additional surface area for bacteria to grow. When used with pond systems, the application is referred to as the Advanced Microbial Treatment System (AMTS). Year-round nitrification has been achieved in an aerated pond in Laurelville, Ohio, and in Canada. Performance data are shown in Table 8.10.

8.5.4.5 Moving Bed Biofilm Reactor™ Process

The Moving Bed Biofilm Reactor™ (MBBR™) is marketed by AnoxKaldnes North America, Inc. (Providence, Rhode Island). The process is similar to the AquaMat except that thousands of small polyethylene wheels are suspended in the pond. With a sufficient number of these wheels, adequate surface area is provided for the growth of nitrifiers. An aerated pond in Johnstown, Colorado, has been successfully upgraded using the MBBR.

TABLE 8.10
Nelson AquaMat® Biomass Carrier, Larchmont, Georgia

Reported Average Effluent Quality (mg/L)	
BOD ₅	6.0
Total suspended solids	10.0
NH ₃	0.1

Source: USEPA, *Biological Nutrient Removal Processes and Costs*, U.S. Environmental Protection Agency, Washington, DC, 2007 (based on Burnett et al., 2004).

8.5.4.6 Poo-Gloo™ (Wastewater Compliance Systems, Inc.)

This patented device, developed at the University of Utah, consists of several concentrically nested domes that provide substrate for bacteria. They are placed on the bottom of a pond, creating a dark environment with robust air and wastewater mixing, which removes contaminants from the water.

8.5.5 OTHER PROCESSES

Partial denitrification has been achieved by most of the systems described above, although the nitrogen removal pathways are not well understood. Several other commercial SBR systems and biomass carrier systems are available. Their use in ponds appears to be limited. The principle is the same, and it appears reasonable to expect these proprietary systems would work. The manufacturers of the products have unique experience working with pond systems. In addition to the products, the companies have experience with floating baffle curtains for partitioning, installation of equipment without removing existing ponds from service, cost-effective and efficient aeration systems for large surface area installations, and optimizing complete mix and partial mix aeration regimes.

8.6 REMOVAL OF PHOSPHORUS

In general, the removal of phosphorus (P) has not been required for wastewaters that receive pond treatment, but there are a number of exceptions for systems in the northcentral United States and Canada. It is expected that phosphorus removal will become a nationwide requirement. The following sections discuss what has been done thus far to control the discharge of phosphorus from wastewater treatment ponds.

8.6.1 BATCH CHEMICAL TREATMENT

In order to meet a phosphorus requirement of 1 mg/L for discharge to the Great Lakes, an approach using in-pond chemical treatment in controlled-discharge ponds was developed in Canada. Alum (hydrated potassium aluminum sulfate), ferric chloride, and lime (calcium oxide) were tested using a motorboat for distribution and mixing of the chemical. A typical alum dosage might be 150 mg/L to produce an effluent from the controlled-discharge pond that contains less than 1 mg/L of phosphorus and less than 20 mg/L BOD₅ and TSS. The sludge buildup from the additional chemicals is insignificant and would allow years of operation before requiring cleaning. The costs for this method were very reasonable and much less than conventional phosphorus removal methods. It has been applied successfully in several Midwestern states (USEPA, 1992). The procedure does require a long-term management plan that includes calibrating applications to minimize use and monitoring sludge quality.

8.6.2 CONTINUOUS-OVERFLOW CHEMICAL TREATMENT

Studies of in-pond precipitation of phosphorus, BOD_5 , and TSS were conducted in Ontario, Canada. The primary objective of the chemical dosing process was to test for the removal of phosphorus with ferric chloride ($FeCl_3$), alum, and lime. Ferric chloride doses of 20 mg/L and alum doses of 225 mg/L, when added continuously to the pond influent, effectively maintained pond effluent phosphorus levels below 1 mg/L over a 2-year period. Hydrated lime at dosages up to 400 mg/L was not effective in consistently reducing phosphorus below 1 mg/L (1 to 3 mg/L was achieved) and yielded no BOD_5 reduction, while slightly increasing the TSS concentration. Ferric chloride reduced effluent BOD_5 from 17 to 11 mg/L and TSS from 28 to 21 mg/L; alum produced no BOD_5 reduction and a slight TSS reduction (from 43 to 28–34 mg/L). Direct chemical addition appears to be effective only for phosphorus removal.

A six-cell pond system located in Waldorf, Maryland, was modified to operate as two three-cell units in parallel. Alum was added to one system, while the other was the control. Each system contained an aerated first cell. Alum addition to the third cell of the system proved to be more efficient in removing total phosphorus, BOD_5 , and TSS than alum addition to the first cell. Total phosphorus reduction averaged 81% when alum was added to the inlet of the third cell and 60% when alum was added to the inlet of the first cell. Total phosphorus removal in the control ponds averaged 37%. When alum was added to the third cell, the effluent total phosphorus concentration averaged 2.5 mg/L, with the control units averaging 8.3 mg/L. Improvements in BOD_5 and TSS removal by alum addition were more difficult to detect, and at times increases in effluent concentrations were observed.

Thirty-seven pond systems in Michigan and Minnesota using chemical treatment to remove phosphorus were studied (USEPA, 1992). In Minnesota, liquid alum was added to the secondary cells of 11 facultative ponds using a motorboat. These ponds were designed with a hydraulic residence time of 180 days and discharge in the spring and fall. The system used is essentially the same as that developed in Ontario, Canada, to achieve a total phosphorus effluent concentration of 1.0 mg/L. Influent concentrations ranged from 1.5 to 6.0 mg/L and averaged approximately 3.3 mg/L. In general, the facilities satisfied the requirement for 1.0 mg/L with several minor excursions outside the limit by 10%. In 2010, 38% of the treatment ponds in Minnesota were treating the wastewater for phosphorus removal (USEPA, 2011). The majority use alum, although other chemicals, such as potassium permanganate, are being evaluated as possible substitutes. All of the ponds are able to meet the phosphorus limit. The chemical is applied twice a year, prior to the seasonal spring and fall discharges.

The State of Michigan evaluated 26 ponds that had been in operation ranging from 1 to 20 years. Both facultative and aerated ponds were evaluated. Discharge was seasonal (once or twice a year) or continuous (varying from 24 hr/day, 7 days/wk to 8 hr/day, 5 days/wk). The chemicals were added to a clarifier following the pond system. None of the systems applied the chemicals by boat. The influent total phosphorus concentration in the Michigan systems ranged from 0.5 to 15 mg/L, with an average of 4.1 mg/L. By 2010, more than 300 wastewater ponds in Michigan had a phosphorus limit of 1 mg/L (USEPA, 2011). Phosphorus removal has been successful as long as

TABLE 8.11
Phosphorus Removal in Ponds

Location	Discharge Schedule	Chemical Treatment	Facility Description	Phosphorus (mg/L)	
				Influent	Effluent
Belding, Michigan	Continuous	Alum	5-Cell pond	4.0	0.6–0.7
Bessemer, Michigan	Continuous with clarifier	Alum polymer	3-Cell pond	1.8–2.0	0.6–0.9
Coppersville, Michigan	Continuous	FeCl ₃	4-Cell pond	5.0	0.3
Kalamazoo Lake, Michigan	Continuous	FeCl ₃ polymer	3-Cell pond	6.0–7.0	0.5–0.6
Elk Rapids, Michigan	Continuous with clarifier	FeCl ₃	3-Cell pond	3.2–4.3	0.6–0.7
Carson City, Michigan	Seasonal	Alum	5-Cell pond	6.0–7.0	4.0
Fowlerville, Michigan	Seasonal	FeCl ₂	6-Cell pond	2.5–3.5	0.8
Remus, Michigan	Seasonal	FeCl ₂	4-Cell pond	4.7	0.4–1.0
Serpent Lake, Minnesota	Seasonal	Alum	3-Cell pond	1.8–2.8	0.6–0.7
Grand Portage, Minnesota	Seasonal	Alum	2-Cell pond	2.9–3.3	0.3–1.2

Source: USEPA, *Phosphorus Removal in Lagoon Treatment Systems*, U.S. Environmental Protection Agency, Chicago, IL, 1992.

the chemical flocculant is added at the appropriate rate at the end of the pond system (i.e., the clarifier or the maturation pond). A description of the facilities and the influent and effluent phosphorus concentrations are shown in Table 8.11.

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9 Improving Pond Effluent

9.1 INTRODUCTION

There are two general ways to improve or upgrade pond effluents: adding a solids removal step or making modifications to the pond process. The selection of the appropriate method to achieve a designed effluent quality depends upon the design conditions and effluent limits imposed on the facility.

9.2 SOLIDS REMOVAL METHODS

The occasional high concentration of total suspended solids (TSS) in the effluent, which can exceed 100 mg/L, has been a major operational challenge to pond systems. The solids are composed primarily of algae and other pond detritus, not wastewater solids. These high concentrations usually occur during the summer months. Solids removal mechanisms include the use of intermittent sand filters, recirculating sand filters, rock filters, coagulation–flocculation, and dissolved air flotation. Nolte & Associates (1992) conducted a review of the literature covering recirculating sand filters and intermittent sand filters.

9.2.1 INTERMITTENT SAND FILTRATION

Intermittent sand filtration applies pond effluent to a sand filter bed on a periodic or intermittent basis. The use of intermittent sand filters has a long and successful history of treating wastewaters (Furman et al., 1955; Grantham et al., 1949; Massachusetts Board of Health, 1912). A summary of the design characteristics and performance of several systems employed in Massachusetts around 1900 is presented in Table 9.1. These systems were treating raw or primary effluent wastewater and producing an excellent effluent. A typical intermittent sand filter is shown in Figure 9.1.

Intermittent sand filtration is capable of polishing pond effluents at relatively low cost and is similar to the practice of slow sand filtration in potable water treatment. As the wastewater passes through the bed, total suspended solids and other organic matter are removed through a combination of physical straining and biological degradation processes. The particulate matter collects in the top 5 to 8 cm (2 to 3 in.) of the filter bed. This accumulation eventually clogs the surface and prevents effective infiltration of additional effluent. At that time, the bed is taken out of service, the top layer of clogged sand is removed, and the unit is put back into service. The removed sand can be washed and reused or discarded.

TABLE 9.1**Design and Performance of Early Massachusetts Intermittent Sand Filters**

Location	Year Started	Loading Rate (gal/day/ac)	Filter Depth (in.)	Sand Size (mm)	Ammonia		BOD ₅ Removal	
					Influent (mg/L)	Effluent (mg/L)	Influent (mg/L)	Effluent (mg/L)
Andover	1902	3500	48–60	0.15–0.2	—	—	—	—
Brockton	—	—	—	—	40.7	1.5	314	6.2
Concord	1899	83,000	—	—	—	—	—	—
Farmington	—	—	70	0.06–0.12	27.3	2.7	—	—
Gardner	1891	122,000	60	0.12–0.18	21.2	7.5	139	9.5
Leicester	—	—	—	—	—	—	321	13.1
Natick	—	—	—	—	12.4	2.3	—	—
Spencer	1897	61,000	48	0.18–0.34	16.0	2.1	116	6.9

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

9.2.1.1 Summary of Performance

Summaries of the performance of intermittent sand filters treating pond effluents conducted during the 1970s and 1980s are presented in Tables 9.2 and 9.3. Table 9.2 is a summary of studies reported in the literature and U.S. Environmental Protection Agency (EPA) documents, and Table 9.3 is a summary of results from field investigations at two full-scale systems consisting of ponds followed by intermittent sand filters. These are the most extensive studies conducted in the United States. Although there are some effluent concentrations above the 30/30 (TSS/BOD₅ mg/L) limit, on the whole the results demonstrate that it is possible to produce an effluent with TSS and BOD₅ less than 15 mg/L from anaerobic, facultative, and aerated ponds followed by intermittent sand filters with effective sizes less than or equal to 0.3 mm.

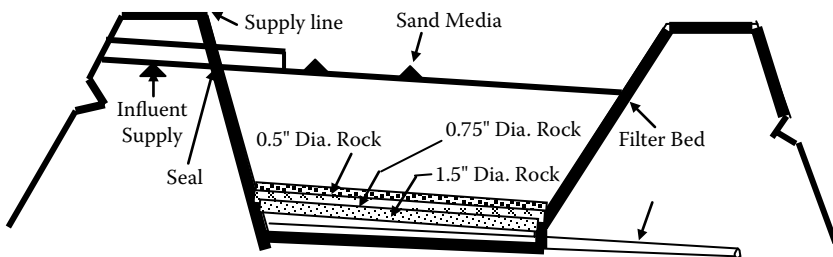


FIGURE 9.1 Cross-sectional view of a typical intermittent sand filter. (From USEPA, *Design Manual: Municipal Wastewater Stabilization Ponds*, EPA 625/1-81-015, U.S. Environmental Protection Agency, Cincinnati, OH, 1983.)

TABLE 9.2**Intermittent Sand Filter Performance Treating Pond Effluents^a**

Pond	Uniformity Constant	Loading Rate (MGD/ac)	TSS Influent (mg/L)	TSS Effluent (mg/L)	TSS Removal (%)	BOD Influent (mg/L)	BOD Effluent (mg/L)	BOD Removal (%)
Facultative	5.80	0.1	13.7	4.0	71	6.3	1.2	82
		0.2	13.7	4.8	65	6.3	1.3	80
		0.3	13.7	6.0	56	6.3	2.0	69
Facultative	9.74	0.2	30.0	3.5	88	19.5	1.9	90
		0.4	30.1	2.9	90	19.5	1.9	90
		0.6	34.0	5.9	83	25.6	4.2	84
		0.8	23.9	4.7	80	2.8	1.8	36
Facultative	6.20	1.0	28.5	5.1	82	13.5	2.6	81
		0.5	32.4	8.6	74	10.7	1.8	83
		1.0	32.4	7.8	76	10.7	2.0	82
Facultative ^b	9.73	1.5	32.4	6.4	80	10.7	2.3	79
		0.3	70.7	10.1	86	20.2	6.6	67
		1.0	68.7	32.9	52	19.6	11.7	40
Aerated	9.73	0.5	158.0	52.5	57	34.4	5.1	85
		1.0	68.7	32.9	52	19.6	11.7	40
Anaerobic	N/A	0.1	353.0	45.5	87	123.0	19.5	64
		0.4	208.0	46.5	78	108.0	43.7	60
		0.5	194.0	45.1	77	107.0	67.6	37
Facultative	9.70	0.2	23.0	2.7	88	10.9	1.1	90
		0.4	20.8	3.5	83	11.5	2.6	77

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

Abbreviations: TSS, total suspended solids; BOD, biochemical oxygen demand.

^a Results for best overall performing 0.17-mm effective size (e.s.) filters.

^b Dairy waste.

It should be noted that the Mt. Shasta Wastewater Treatment plant retired the intermittent sand filter bed and has been using dissolved air flotation to remove algae since 2000. The treatment process consists of headworks, four oxidation ponds, ballast lagoon dosing basin, dissolved air flotation system, intermittent backwash filter, chlorine contact chamber, dechlorination system, and discharge line. The treated wastewater can be discharged to any of three locations, depending on water quality and time of year: (1) the Sacramento River, (2) a leach field located adjacent to Highway 89, or (3) the Mt. Shasta Resort Golf Course.

Rich and Wahlberg (1990) evaluated the performance of five facultative pond–intermittent sand filter systems located in South Carolina and Georgia. A summary of the design characteristics and performance of these systems is shown in Table 9.4.

TABLE 9.3**Mean Performance Data for Three Full-Scale Pond–Intermittent Sand Filter Systems**

Parameter	Mt. Shasta, California			Moriarty, New Mexico		
	Pond Effluent	Filter Effluent	Facility Effluent	Pond Effluent	Filter Effluent	Facility Effluent
BOD ₅ (mg/L)	22.0	11.0	8.00	30.0	17.00	17.0
Soluble BOD ₅ (mg/L)	7.0	4.0	5.00	17.0	16.00	16.0
TSS (mg/L)	49.0	18.0	16.00	81.0	13.00	13.0
VSS (mg/L)	34.0	13.0	10.00	64.0	9.00	9.0
Fecal coliform (col/100 mL)	292.0	30.0	<2.00	290.0	18.00	34.0
pH	87.0	68.0	66.00	8.9	8.00	8.0
DO (mg/L)	12.4	5.5	5.30	10.9	8.30	8.3
COD (mg/L)	100.0	87.0	68.00	84.0	43.00	43.0
Soluble COD (mg/L)	71.0	64.0	50.00	67.0	34.00	34.0
Alkalinity (mg/L as CaCO ₃)	75.0	51.0	42.00	293.0	260.00	260.0
TP (mg/L P)	3.9	3.1	2.70	4.0	2.80	2.8
TKN (mg/L N)	11.1	7.5	5.20	22.0	121.00	121.0
NH ₃ (mg/L N)	5.6	1.8	1.80	16.0	9.16	9.2
Organic N (mg/L N)	56.0	5.7	3.40	5.7	3.30	3.3
NO ₂ ⁻ (mg/L N)	0.6	7.7	0.02	159.0	1.66	1.7
NO ₃ ⁻ (mg/L N)	0.8	43.0	45.00	0.1	4.09	4.1
Total algae count	4 × 10 ⁵	1 × 10 ⁵	1 × 10 ⁵	8 × 10 ⁵	3 × 10 ⁴	3 × 10 ⁴
Flow (MGD)	NA	NA	0.49	NA	0.05	NA

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

Note: NA = not available.

The systems provided superior performance when compared with ten aerated pond systems not using intermittent sand filtration. Six of the 10 aerated pond systems consisted of one aerated cell followed by a polishing pond: three were designed as dual-power (aeration reduced in succeeding cells), multicellular systems, and one was a single-cell dual-power system. Using data reported by Niku et al. (1981), the performance of the facultative pond–intermittent sand filter systems compared favorably with activated sludge plants.

Truax and Shindala (1994) reported the results of an extensive evaluation of facultative pond–intermittent sand filter systems using four grades of sand with effective sizes of 0.18 to 0.70 mm and uniformity coefficients ranging from 1.4 to 7.0. Performance was directly related to the effective size of the sand and hydraulic loading rate. With effective size sands of 0.37 mm or less and hydraulic loading rates of 0.2 m³/m²/day, effluents with BOD₅ and TSS of less than 15 mg/L were obtained. Total Kjeldahl nitrogen (TKN) concentrations were reduced from 11.6 mg/L to

TABLE 9.4**Design Characteristics and Performance of Facultative Pond–Intermittent Sand Filter Systems**

Design Flow (m ³ /L)	Present Flow (% of Design)	Hydraulic Retention Time (days)	Filter Dosing ^a (m ³ /m ² /day)	BOD ₅ (g/m ³)		TSS (g/m ³)		NH ₃ (g/m ³)	
				50%	95%	50%	95%	50%	95%
303	56	93	0.03	9	28	12	41	0.9	4.0
303	79	70	0.37	6	22	7	29	0.4	1.2
568	48	59	0.47	7	17	11	30	—	—
378	66	52	0.37	9	21	11	25	0.9	2.4
568	37	55	0.31	6	17	6	16	1.3	5.4

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

^a Based on design flow rate.

4.3 mg/L at the 0.2-m³/m²/day loading rate. The experiments were conducted in a mild climate, and it is not known whether similar nitrogen removal rates would be achieved during cold months in more severe climates.

Melcer et al. (1995) reported the performance of a full-scale aerated pond–intermittent system located in New Harrisburg, Ontario, that had been in operation since 1980. Results for 1990 and for January to August of 1991 are presented in Table 9.5. Surface loading rates for both periods were 3.24 m³/m²/day, with influent BOD₅, TSS, and TKN concentrations of 12, 16, and 19 mg/L, respectively. Filter effluent quality exceeded requirements, with BOD₅, TSS, and TKN concentrations being less than 2 mg/L.

9.2.1.2 Operating Periods

Several publications contain extensive information on the relationship between solids deposited on the surface of a filter and the length of run time (Bishop et al., 1977; Earnest et al., 1978; Hill et al., 1977; Marshall and Middlebrooks, 1974; Messinger, 1976; Russell et al., 1983; Tupy et al., 1979; USEPA, 1983a). Truax and Shindala (1994) also reported similar run times. The standard rule of thumb presented in this text, and generally accepted as the industry standard, states that the length of a filter run is a function of the effective size of the sand and the quantity of solids deposited on the surface of the filter.

9.2.1.3 Maintenance Requirements

Maintenance is directly related to the quantity of solids applied to the surface of the filter, and this is related to the concentration of solids in the influent to the filter and the hydraulic loading rate. Filters with low hydraulic loading rates tend to operate for extended periods. With such extended operating periods, maintenance

TABLE 9.5
Performance of Aerated Pond–Intermittent Sand Filter,
New Hamburg, Ontario Plant

Location in System	Parameter	1990	1991 (Jan-Aug)
Influent	Average flow rate (m ³ /day)	1676	1673
	Maximum flow rate (m ³ /day)	4530	3990
	BOD ₅ (mg/L)	186	120
	TSS (mg/L)	314	171
	TKN (mg/L)	45	44
Aerated cell	TP (mg/L)	9	10
	HRT (days)	7	7
	BOD ₅ loading (kg/m ³ /day)	0.03	0.02
Aerated cell effluent	BOD ₅ (mg/L)	34	36
	TSS (mg/L)	44	44
	TP (mg/L)	6	5
Facultative pond	HRT (days)	165	165
	Avg. BOD ₅ loading (kg/1000 m ² /day)	0.51	0.55
Cell 2 effluent	BOD ₅ (mg/L)	12	11
	TSS (mg/L)	16	18
	TKN (mg/L)	19	18
	NH ₃ (mg/L)	15	14
	TN (mg/L)	1	1
Filter	TP (mg/L)	1	1
	Annual surface loading (m ³ /m ²)	195	153
	Surface loading (L/m ² /day)	3240	3240
		Mar–Dec	Mar–Aug
Filter effluent	BOD ₅ (mg/L)	2.0	2.0
	TSS (mg/L)	1.7	1.1
	TKN (mg/L)	2.0	1.1
	NH ₃ (mg/L)	1.2	0.6
	TN (mg/L)	7.0	9.0
	TP (mg/L)	0.5	0.4

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

consists of routine inspection of the filter, removing weeds, and an occasional cleaning by removing the top 5 to 8 cm of sand after allowing the filter to dry out. Early control of weeds is the key to good maintenance. The use of chemicals is not advised. In Wisconsin, where there are many sand filters, the operations and maintenance (O&M) manuals advise that the sand beds can be tilled if the weeds are very small. Once they have grown, however, they need to be removed manually (USEPA, 2011).

9.2.1.4 Hydraulic Loading Rates

Typical hydraulic loading rates on a single-stage filter range from 0.37 to 0.56 m³/m²/day. If the TSS in the influent to the filter routinely exceeds 50 mg/L, the hydraulic loading rate should be reduced to 0.19 to 0.37 m³/m²/day to increase the filter run. In cold weather locations, the lower end of the range is recommended to avoid having to clean the filter during the winter months.

9.2.1.5 Design of Intermittent Sand Filters

Algae removal from pond effluent is almost totally a function of the sand size used. With a required BOD₅ and TSS below 30 mg/L, a single-stage filter with medium sand (effective size = 0.3 mm) will produce a reasonable filter run. If better effluent quality is required, finer sand (effective size, 0.15 to 0.2 mm) or a two-stage filtration system with the finer sand in the second stage should be used.

The total filter area required for a single-stage operation is calculated by dividing the expected influent flow rate by the hydraulic loading rate selected for the system. One spare filter unit should be included to permit continuous operation, as the cleaning process may require several days. An alternative approach is to provide temporary storage in the pond units. Three filter beds are the preferred arrangement to permit maximum flexibility. In small systems that depend on manual cleaning, the individual bed should not be bigger than about 90 m (969 ft²). Larger systems with mechanical cleaning equipment could have individual filter beds up to 5000 m² (53,820 ft²).

The design depth of sand in the bed should be at least 45 cm (17.7 in.) with a sufficient depth for at least one year of cleaning cycles. A single cleaning operation may remove 2.5 to 5 cm (1 to 2 in.) of sand. A 30-day filter run would then require an additional 30 cm (11.8 in.) of sand. In the typical case, an initial bed depth of about 90 cm (35.4 in.) of sand is usually provided. A graded gravel layer 30 to 45 cm (11.8 to 17.7 in.) deep separates the sand layer from the under drains. The bottom layer is graded so that its effective size is four times as great as the openings in the under-drain piping. The successive layers of gravel are progressively finer to prevent intrusion of sand. An alternative is to use gravel around the underdrain piping and then a permeable geotextile membrane to separate the sand from the gravel. Further details on design and performance are presented in USEPA (1983), Reed et al. (1995), and Crites et al. (2006).

9.2.2 ROCK FILTERS

A rock filter operates by allowing pond effluent to travel through a submerged porous rock bed, causing algae to settle out on the rock surfaces as the liquid flows through the void spaces. The accumulated algae are then biologically degraded. Algae removal with rock filters has been studied extensively at Eudora, Kansas, and Veneta, Oregon, and in California and Missouri (USEPA, 1983). Rock filters have been installed throughout the United States and the world, and performance has varied (Middlebrooks, 1988; Saidam et al., 1995; USEPA, 1983). A diagram of the Veneta rock filter is shown in Figure 9.2. The West Monroe, Louisiana, rock filters were essentially the same as the one in Veneta, but the filters received higher loading rates. Several rock filters of various designs have been constructed in Illinois

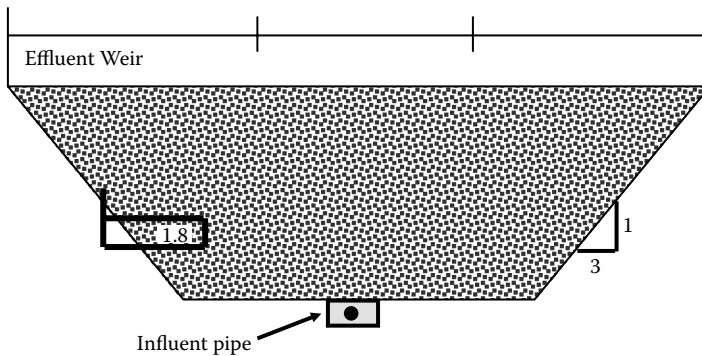


FIGURE 9.2 Rock filter at Veneta, Oregon. (Adapted from Swanson, G.R. and Williamson, K.J., *J. Environ. Eng. Div.*, 106(EE6), 1111–1119, 1980.)

with varied success. Many of the Illinois filters have produced an excellent effluent, but the designs vary widely (USEPA, 2011). Figure 9.3 contains diagrams of the various types of rock filters in use in Illinois. K.E. Snider designed a rock filter for Pineville, Oregon, and knew of one built at Harrisburg, Oregon. Performance and design details are not available, but USEPA via personal communication with Snider indicated that the systems were designed using information from the Veneta system.

The principal advantages of the rock filter are the relatively low construction costs and simple operation. Odor problems can occur, and the design life for the filters and the cleaning procedures have not yet been firmly established. Several units have been operating successfully for over 20 years. Archer and O'Brien (2005) have used interpond rock filters to improve suspended solids and nitrogen removal. Rock embankments across the ponds provide filtering, reduce short-circuiting, and increase the surface area for growing nitrifying bacteria.

9.2.2.1 Veneta, Oregon, Rock Filter System

Based on data from filter systems in place in Veneta, it can be concluded that rock filter performance is mixed. Performance data for 1994 are shown in Table 9.6. After approximately 20 years of operation, the system was producing an effluent meeting secondary standards with regard to BOD₅, TSS, and fecal coliform. Ammonia data were not collected routinely as it was not included in the discharge permit. Ammonia data were only collected on a regular basis during the winter months of the Swanson and Williamson (1980) study, and high NH₃ concentrations were observed in the effluent. Occasional NH₃ measurements were made after the Swanson and Williamson study, and higher concentrations were observed during the winter, indicating that the process may not be suitable if a discharge must meet NH₃ effluent limits.

9.2.2.2 West Monroe, Louisiana

Stamberg et al. (1984) presented performance results of the two rock filters operating in West Monroe, Louisiana. The systems were loaded at higher hydraulic loading rates than that used for the Veneta facility ($<0.3 \text{ m}^3$ of wastewater per day per rock m^3), and

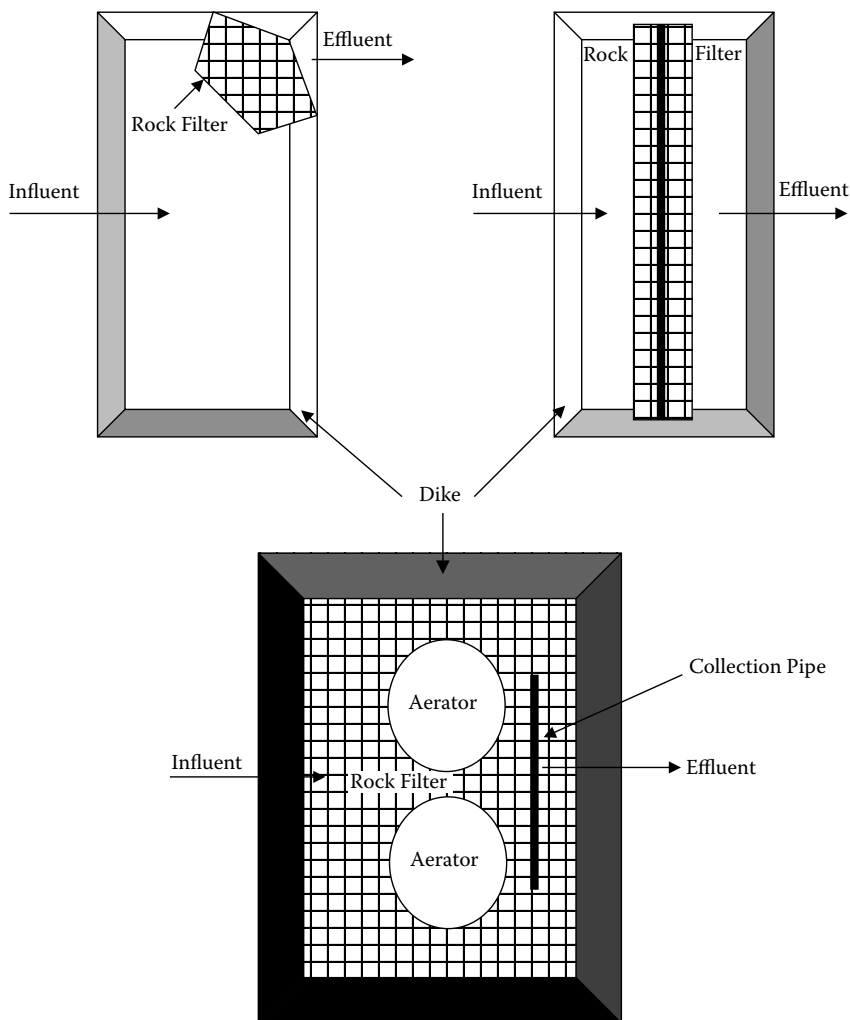


FIGURE 9.3 State of Illinois rock filter configurations. (Adapted from USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.)

the TSS removals were less than those reported for the Veneta system. In general, the West Monroe systems produced effluent BOD_5 and TSS concentrations less than 30 mg/L, but while there were occasional exceedances of BOD_5 to 40 mg/L and TSS to 50 mg/L, only 12 out of over 100 samples exceeded 30 mg/L for either parameter. The design flow rates on the West and East filters were 3.5 and 1.8 MGD, respectively, and the flow rates frequently exceeded the design rate by a factor of 2 to 3. This resulted in an increase in the loading rate by a factor of 2 to 3, which greatly exceeded the Veneta loading rate.

TABLE 9.6
Mean and Range of Performance Data for Veneta
Wastewater Treatment Plant (1994)

Constituent	Influent	Effluent
BOD ₅ (mg/L)	138 (50–238)	17 (5–30)
TSS (mg/L)	124 (50–202)	9 (2–27)
Fecal coliform (MPN/100 mg/L)	Not available	<10 (<10–20)
Flow (MGD)	0.251 (0.159–0.452)	0.309 (0.079–0.526)

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

9.2.2.3 Jordan Rock Filters

Saidam et al. (1995) performed a series of studies of rock filters treating pond effluent in Assram, Jordan. The filters were arranged in three trains, the first train consisting of two filters in series, with the first filter containing rock and having an average diameter of 18 cm, followed by a filter containing local gravel (wadi gravel) with an average diameter of 11.6 cm. The second train contained the same rock as used in the first filter, but with an average diameter of 2.4 cm. The wadi gravel was used in the first filter of the third train, and the second filter contained an aggregate with an average diameter of 1.27 cm. The filters in the three trains were operated in series, and the characteristics of the wastewater, hydraulic loading rates, and effluents from the various filters are shown in Table 9.7. The removal efficiencies obtained in the first run for the various filters and the trains are summarized in Table 9.8. Even though the rock sizes of several of the filters were similar to what was used at Veneta and West Monroe, the hydraulic loading rates exceeded the maximum recommended value of 0.3 mg³/m²/day, and the quality of the effluents was much lower. There was insufficient dissolved oxygen (DO) in the influent to oxidize NH₃, and, considering the temperature of the influent wastewater and the H₂S in the effluent, it is likely that the filters were anaerobic. On the other hand, TSS was lowered by 60% and fecal coliform levels met FAO guidelines for unrestricted use of the effluent for agricultural purposes (FAO, 2003).

9.2.2.4 New Zealand Rock Filters

Rock filters have been used in New Zealand for removing high concentrations of algae from pond effluents (Middlebrooks et al., 2005). The systems were developed from subsurface-flow wetlands without plants. The rock ranges from 12 to 24 cm in diameter, with the coarser rocks at the inlet and outlet to distribute the flow evenly. Rock filters are generally anoxic, and there is little nitrification; however, there can be denitrification. The effluent is anaerobic and does emit H₂S on occasion. If the influent contains high concentrations of algae, organic nitrogen will increase in the effluent. Three systems in New Zealand use steel slag, which has a high porosity

TABLE 9.7
Performance of Rock Filters

Unit	Hydraulic Loading Rate (m ³ /m ² /day)	Run	Temp. (°C)	DO (mg/L)	TSS (mg/L)	BOD ₅ (mg/L)
Influent						
		1	25.7	3.2	201	95
		2	21.0	4.8	234	105
		3	14.0	4.0	213	122
		4	15.0	3.5	101	108
First Train						
Rock filter 1	0.498	1	25.1	1.2	131	61
Avg. diameter = 18 cm	0.634	2	20.0	1.5	200	81
Voids = 49%	0.5–0.58	3	13.4	1.0	156	100
Surface area = 17 m ² /m ³	0.5–0.58	4	13.0	2.1	76	77
Wadi gravel filter 1	0.386	1	25.2	1.9	78	36
Avg. diameter = 11.6 cm	0.634	2	—	—	161	66
Voids = 41%	0.5–0.58	3	13.4	1.0	129	77
Surface area = 25 m ² /m ³	0.5–0.58	4	13.0	1.9	66	74
Second Train						
Rock filter 2	0.311	1	25.3	1.1	130	53
Avg. diameter = 18 cm	0.634	2	19.7	1.4	203	79
Voids = 49%	0.5–0.58	3	13.3	1.0	164	87
Surface area = 17 m ² /m ³	0.5–0.58	4	13.7	1.9	88	92
Coarse aggregate filter 2	0.333	1	25.6	1.7	102	51
Avg. diameter = 2.4 cm	0.634	2	19.9	1.4	154	65
Voids = 40%	0.5–0.58	3	13.3	1.0	134	73
Surface area = 150 m ² /m ³	0.5–0.58	4	15.0	1.9	60	87
Third Train						
Wadi gravel filter 3	0.274	1	25.7	1.6	109	48
Avg. diameter = 11.6 m	0.634	2	20.2	1.4	206	76
Voids = 41%	0.5–0.58	3	13.3	1.0	150	86
Surface area = 25 m ² /m ³	0.5–0.58	4	15.0	1.9	81	76
Medium aggregate filter 3	0.442	1	25.9	2.0	79	42
Avg. diameter = 1.27 cm	0.634	2	19.7	1.5	121	72
Voids = 28%	0.5–0.58	3	13.4	1.0	108	66
Surface area = 327 m ² /m ³	0.5–0.58	4	13.0	1.9	45	59

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

TABLE 9.8
Summary of Removal Efficiency in the First Run

Parameter	Percent Removal of Individual Filters						% Removal Per Train		
	Rock	Wadi	Rock	Coarse	Wadi	Medium	First	Second	Third
	Filter 1	Gravel Filter 1	Filter 2	Aggregate Filter 2	Gravel Filter 3	Aggregate Filter 3			
TSS	34	41	35	22	46	25	61	49	59
BOD ₅	36	41	44	4	49	13	62	46	56
COD	19	18	21	15	24	25	33	33	44
Total phosphorus	9	15	9	30	18	33	24	35	46
Total fecal coliform	80	55	83	21	85	60	90	86	94
Color	25	34	28	20	30	36	51	42	55

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

and produces less H₂S. Some phosphorus removal was observed for the first years of operation. The filters follow partial mix aerated ponds and have consistently produced TSS effluent concentrations less than 25 mg/L. Average removals have been less than 12 mg/L, even when influent solids were 100 mg/L or greater.

9.2.2.5 Design of Rock Filters

Rock filters have been designed using a number of parameters. A summary of the design parameters used for several locations is shown in Table 9.9. The critical factor in the design of rock filters appears to be the hydraulic loading rate. Rates less than 0.3 m³/m²/day give the best results with rocks in the range of 8 to 20 cm and a depth of 2 m with the water applied in an upflow pattern.

9.2.2.6 Aerated Rock Filter

To address the lack of NH₃ removal in rock filters, Mara and Johnson (2006) constructed an aerated rock filter with perforated pipe placed in the underdrain. They operated the aerated rock filter in parallel with a non-aerated control over an 18-month period. Facultative pond effluent containing approximately 10 mg/L of NH₃ was applied to the filters at a hydraulic rate of 150 L/m²/day during the first 8 months of operation and at 300 L/m²/day thereafter. Ammonia concentrations in the aerated filter effluent were less than 3 mg/L, and NO₃⁻ concentrations were approximately 5 mg/L, while the control filter nitrogen concentrations were approximately 7 mg/L. Ammonia removal did not occur in the non-aerated control, and there was a

TABLE 9.9
Design Parameters for Rock Filter Systems in the United States

Parameter	Veneta, Oregon	W. Monroe, Louisiana	Illinois	Eudora, Kansas	California
Hydraulic loading rate (m ³ /m ² /day)	0.3	0.36	0.8	≤1.2	0.4
Rock (cm)	7.5–20	5–13	8–15 Free of fines Soft weathering stone No flat rock	2.5	6–13
Aeration	None	None	Post-aeration ability necessary	None	None
Depth (m)	2	1.8	Rock media must extend 0.3 m above water surface	1.5	1.68
Disinfection	Yes	Yes	Chlorination of post-aeration cell encouraged	Not applicable	Yes

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

statistically significant increase in the mean NH₃ concentration between the influent and effluent. Fecal coliform concentrations were reduced in the aerated filter from 103 to 104 per 100 mg/L to a geometric mean count of 65 per 100 mL. BOD₅ and TSS removals were higher in the aerated filter. The 95th-percentile effluent concentrations in the aerated filter were 9 and 10 mg/L, respectively, while the effluent concentrations from the control were 38 and 43 mg/L.

Increasing the hydraulic loading rate from 150 to 300 L/m²/day did not negatively affect the mean percentage BOD₅, NH₃, and fecal coliform removals. There was a slight reduction in the TSS removals. It was concluded that the use of aerated rock filters eliminates the need for maturation ponds to remove NH₃ and reduces the surface area required for maturation ponds at a flow rate of 200 L/person/day from approximately 5 m²/person to 1.3 m²/person with an aerated rock filter 0.5 m deep and loaded at 300 L/m²/day. In winter, the facultative pond DO concentration was approximately 2 mg/L and approximately 8 mg/L in the aerated filter effluent. The control non-aerated filter effluent DO concentration was approximately 1 mg/L.

In a follow-up study, Johnson and Mara (2007) conducted studies comparing a pilot-scale subsurface horizontal flow constructed wetland, a non-aerated rock filter, and an aerated rock filter receiving effluent from a facultative pond loaded at 79 kg/ha/day. BOD₅, TSS, and NH₃ concentrations were lower in the effluent from the aerated rock filter when compared with the non-aerated rock filter and the constructed wetland (USEPA, 2011).

9.2.3 NORMAL GRANULAR MEDIA FILTRATION

Granular media filtration (rapid sand filters) separates liquids and solids. The simple design and operation process make it applicable to wastewater streams containing up to 200 mg/L suspended solids. The process can be automated based on easily measured parameters with minimum operation and maintenance costs. On the other hand, regular granular media filtration is not as efficient for removing algae unless coagulants or flocculants have been added prior to filtration. Table 9.10 contains a summary of the results with direct general media filtration. Diatomaceous earth filtration is capable of producing a high-quality effluent when treating wastewater treatment pond water, but the filter cycles are generally less than 3 hours. This results in excessive usage of backwash water and diatomaceous earth, which increases costs and eliminates this method of filtration as an alternative for polishing wastewater treatment pond effluents.

9.2.4 COAGULATION–FLOCCULATION

Following screening and the other pretreatment processes, the next unit process in a conventional water treatment system is a mixer where the first chemicals are added in what is known as coagulation. The exception to this situation occurs in small systems using groundwater, when chlorine or other taste and odor control measures are introduced at the intake and are the extent of treatment. The term coagulation refers to the series of chemical and mechanical operations by which coagulants are

TABLE 9.10
Summary of Direct Filtration with Rapid Sand Filters

Investigators	Coagulant	Filter Loading (gpm/ft ²)	Filter Depth (cm)	Sand Size (mm) ^a	Findings
Borchardt and O'Melia (1961)	None	0.2–2	61	d ₅₀ = 0.32	50% algae removal;
	Fe	2.1	61	d ₅₀ = 0.40	removal declines to
	(7 mg/L)				21–45% after 15 hr
Davis and Borchardt (1966)	None	0.49	—	d ₅₀ = 0.75	22% algae removal
	None	0.49	—	d ₅₀ = 0.29	34% algae removal
	None	1.9	—	d ₅₀ = 0.75	10% algae removal
	None	1.9	—	d ₅₀ = 0.29	2% algae removal
	Fe	—	—	d ₅₀ = 0.75	45% algae removal
Foss and Borchardt (1969)	None	2	91	d ₅₀ = 0.71	pH 2.5; 90% removal
Lyman et al. (1969)	None	1.1	28	d ₅₀ = 0.55	62% TSS removal
Kormanki and Cravens (1978)	None	—	—	—	11–45% TSS removal

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

^a d₅₀ = Diameter of 50% of sand.

applied and made effective. These operations are comprised of two distinct phases: (1) rapid mixing to disperse coagulant chemicals by violent agitation into the water being treated, and (2) flocculation to agglomerate small particles into well-defined floc by gentle agitation for a much longer time. The coagulant must be added to the raw water and perfectly distributed into the liquid; such uniformity of chemical treatment is reached through rapid agitation or mixing.

Coagulation results from adding salts of iron or aluminum to the water. Common coagulants (salts) are as follows:

- Alum (aluminum sulfate)
- Sodium aluminate
- Ferric sulfate
- Ferrous sulfate
- Ferric chloride
- Polymers

Coagulation is the reaction between one of these salts and water.

Flocculation follows coagulation in the conventional water treatment process. Flocculation is the physical process of slowly mixing the coagulated water to increase the probability of particle collision. Through experience, we see that effective mixing reduces the required amount of chemicals and greatly improves the sedimentation process, which results in longer filter runs and higher quality finished water. The goal of flocculation is to form a uniform, feather-like material similar to snowflakes—a dense, tenacious floc that entraps the fine, suspended, and colloidal particles and carries them down rapidly in the settling basin. To increase the speed of floc formation and the strength and weight of the floc, polymers are often added.

Coagulation has been applied extensively for the removal of suspended and colloidal materials from water. Lime, alum, and ferric salts are the most commonly used coagulating agents. Floc formation is sensitive to parameters such as pH, alkalinity, turbidity, and temperature. Most of these variables have been studied, and their effects on the removal of water supply turbidity have been evaluated. In the case of the chemical treatment of wastewater treatment pond effluents, however, the data are not comprehensive.

Shindala and Stewart (1971) investigated chemical treatment of treatment pond effluents as a post-treatment process to remove the algae and to improve the quality of the effluent. They found that the optimum dosage for best removal of the parameters studied was 75 to 100 mg/L of alum. When this dosage was used, the removal of phosphate was 90% and the BOD₅ was 70%.

Tenney (1968) showed that, at a pH range of 2 to 4, algal flocculation was effective when a constant concentration of a cationic polyelectrolyte (10 mg/L of C-31) was used. Golueke and Oswald (1965) conducted a series of experiments to investigate the relationship of hydrogen ion concentrations to algal flocculation. In this study, only H₂SO₄ (sulfuric acid) was used, and only to lower the pH. They found that flocculation was most extensive at a pH value of 3, which agrees with Tenney's results, and they reported algal removals of about 80 to 90%. Algal removal efficiencies by cationic polyelectrolytes were not affected in the pH range of 6 to 10.

DID YOU KNOW?

To determine the correct chemical dosage, a *jar test* or *coagulation test* is performed. Jar tests (widely used for many years by the water treatment industry) simulate full-scale coagulation and flocculation processes to determine optimum chemical dosages. It is important to note that jar testing is only an attempt to achieve a ballpark approximation of correct chemical dosage for the treatment process. The test conditions are intended to reflect the normal operation of a chemical treatment facility. The test can be used to

- Select the most effective chemical.
- Select the optimum dosage.
- Determine the value of a flocculant aid and the proper dose.

The California Department of Water Resources (1971) reported that of 60 polyelectrolytes tested, 17 compounds were effective with regard to coagulation of algae and were economically competitive when compared to mineral coagulation used alone. Generally, a dose of less than 10 mg/L of the polyelectrolytes was required for effective coagulation. A daily addition of 1 mg/L of FeCl_3 to the algal growth pond resulted in significant reductions in the required dosage of both organic and inorganic coagulants.

McGarry (1970) studied the coagulation of algae in treatment pond effluents and reported the results of a complete factorial designed experiment using the common jar test. Tests were performed to determine the economic feasibility of using polyelectrolytes as primary coagulants alone or in combination with alum. McGarry also investigated some of the independent variables that affected the flocculation process, such as concentration of alum, flocculation turbulence, concentration of polyelectrolytes, pH after the addition of coagulants, chemical dispersal conditions, and high-rate oxidation pond suspension characteristics. Alum was found to be effective for coagulation of algae from high-rate oxidation pond effluent. The lowest cost per unit algal removal was obtained with alum alone (75 to 100 mg/L).

Al-Layla and Middlebrooks (1975) evaluated the effects of temperature on algae removal using coagulation–flocculation–sedimentation. Removal at a given alum dosage decreased as the temperature increased. Maximum algae removal generally occurred at an alum dosage of approximately 300 mg/L at 10°C. At higher temperatures, alum dosages as high as 600 mg/L did not produce removals equivalent to the results obtained at 10°C with 300 mg/L of alum. The settling time required to achieve significant removals, flocculation time, organic carbon removal, total phosphorus removal, and turbidity removal were found to vary inversely as the temperature of the wastewater increased.

Dryden and Stern (1968) and Parker (1976) reported on the performance and operating costs of a coagulation–flocculation system followed by sedimentation, filtration, and chlorination, with discharge to recreational lakes. This system, in Lancaster, California, probably has the longest operating record of any coagulation–flocculation

system treating wastewater treatment pond effluent. The TSS concentrations of influent coming to the plant have ranged from about 120 to 175 mg/L, and the plant has produced an effluent with a turbidity of less than 1 Jackson turbidity unit (JTU) or Jackson candle method most of the time.* Aluminum sulfate ($\text{Al}_2(\text{SO}_4)_3$) dosages have ranged from 200 to 360 mg/L. The design capacity is 1893 m³/day (0.5 MGD).

The coagulation–flocculation process is not easily controlled and requires operating personnel at all times. A large volume of sludge may be produced, which can introduce an additional operating cost.

9.2.5 DISSOLVED AIR FLOTATION

Dissolved air flotation (DAF) is a water treatment process that clarifies wastewater (or other waters) by the removal of suspended matter such as solids (e.g., algae). The removal is achieved by dissolving air in the water or wastewater under pressure and then releasing the air at atmospheric pressure in a flotation tank or basin. The released air forms tiny bubbles, which adhere to the suspended matter and cause the suspended matter to float to the surface of the water, where it may then be removed by a skimming device (Beychok, 1967; Kiuru and Vahala, 2000; Spellman, 2013; Wang et al., 2004). Several studies have shown the dissolved air flotation process to be an efficient and a cost-effective means of algae removal from wastewater treatment pond effluents. The performance obtained in several of these studies is summarized in Table 9.11.

Three basic types of dissolved air flotation are employed to treat wastewaters: total, partial, and recycle pressurization. These three types are illustrated in Figure 9.4. In the total pressurization system, the entire wastewater stream is injected with air, pressurized, and held in a retention tank before entering the flotation cell. The flow is direct, and all recycled effluent is repressurized. In partial pressurization, only part of the wastewater stream is pressurized, and the remainder of the flow bypasses the air dissolution system and enters the separator directly. Recycling serves to protect the pump during periods of low flow, but it does load the separator hydraulically. Partial pressurization requires a smaller pump and a smaller pressurization system. In recycle pressurization, clarified effluent is recycled for the purpose of adding air and then is injected into the raw wastewater. Approximately 20 to 50% of the effluent is pressurized in this system. The recycle flow is blended with the raw water flow in the flotation cell or in an inlet manifold.

Important parameters in the design of a flotation system are hydraulic loading rate (including recycle), concentration of TSS contained within the flow, coagulant dosage, and the air-to-solids ratio required to achieve efficient removal. Pilot-plant studies by Stone et al. (1975), Bare (1971), and Snider (1976) showed that the maximum hydraulic loading rate ranged between 81.5 and 101.8 L/min/m². The most efficient air-to-solids ratio was found to be 0.019 to 1.0 (Bare, 1971). Solids concentrations during Bare's studies were 125 mg/L. Experimental results with the removal

* The Jackson turbidity unit is essentially the inverse measure of the length of a column of water needed to completely obscure a candle flame viewed through it. The more water needed (the longer the water column), the clearer the water.

TABLE 9.11
Summary of Typical Dissolved Air Flotation Performance

Reference	Location	Coagulant and Dose (mg/L)	Overflow Rate (gpm/ft ²)	Detention Time (minutes)	BOD ₅		
					Influent (mg/L)	Effluent (mg/L)	Percent (%) Removed
Parker (1976)	Stockton, California	Alum, 225 acid added to pH 6.4	2.7 ^a	17 ^a	46	5	89
Ort (1972)	Lubbock, Texas	Lime, ^c 150	NA	12 ^b	280–450	1.3	>99
Komline- Sanderson (1972)	Eldorado, Arizona	Alum, 200	4.0 ^c	8 ^c	93	<3	<97
Bare (1971)	Logan, Utah	Alum, 300	1.3–2.4 ^d	NA	NA	NA	NA
Stone et al. (1975)	Sunnyvale, California	Alum, 175 acid added to pH 6.0–6.3	2.0 ^e	11 ^e	NA	NA	NA
Parker (1976)	Stockton, California	Alum, 225 acid added to pH 6.4	2.7 ^a	17 ^a	104	20	81
Ort (1972)	Lubbock, Texas	Lime, ^c 150	NA	12 ^b	240–360	0–50	>79
Komline- Sanderson (1972)	Eldorado, Arizona	Alum, 200	4.0 ^c	8 ^c	450	36	92
Bare (1971)	Logan, Utah	Alum, 300	1.3–2.4 ^d	NA	150	30	96
Stone et al. (1975)	Sunnyvale, California	Alum, 175 acid added to pH 6.0–6.3	2.0 ^e	11 ^e	150	30	80

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

^a 33% pressurized (35–60 psi) recycle.
^b 30% pressurized (50 psi) recycle.
^c 100% pressurized recycle.
^d 25% pressurized (45 psi) recycle.
^e 27% pressurized (55–70 psi) recycle.

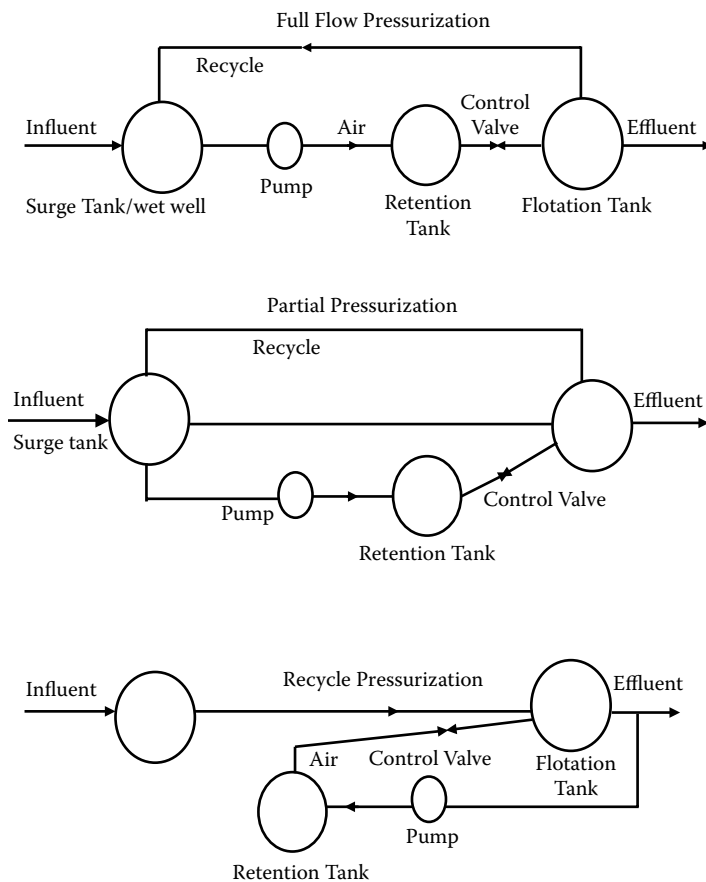


FIGURE 9.4 Types of dissolved air flotation systems. (Adapted from USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.)

of algae indicate that lower hydraulic rates and air-to-solids ratios than those recommended by the manufacturers of industrial equipment should be employed when attempting to remove algae.

In combined sedimentation flotation pilot-plant studies at Windhoek, Namibia, van Vuuren and van Duuren (1965) reported effected hydraulic loading rates ranging between 11.2 and 30.5 L/min/m², with flotation provided by the naturally dissolved gases. Because air was not added, air-to-solids ratios were not reported. They also noted that it was necessary to use from 125 to 175 mg/L of $\text{Al}_2(\text{SO}_4)_3$ to flocculate the effluent containing from 25 to 40 mg/L of algae. Subsequent reports on a total flotation system by van Vuuren et al. (1965) stated that a dose of 400 mg/L

of $\text{Al}_2(\text{SO}_4)_3$ was required to flocculate a 110-mg/L algal suspension sufficiently to obtain a removal that was satisfactory for consumptive reuse of the water. Based on data provided by Parker et al. (1973), Stone et al. (1975), Bare (1971), and Snider (1976), it appears that a much lower dose of alum can be applied to produce an effluent that will meet current discharge standards.

Dissolved air flotation with the application of coagulants performs essentially the same function as coagulation–flocculation–sedimentation, except that a much smaller system is required with the flotation device. Flotation will occur in shallow tanks with hydraulic retention times of 7 to 20 min, compared with hours in deep sedimentation tanks. Overflow rates can be as high as 81.5 to 101.8 L/min-m² with flotation, whereas a value of less than 407 L/min-m² is recommended with sedimentation. However, it must be pointed out that the sedimentation process is much simpler to operate and maintain than the flotation process, and when applied to small systems consideration must be given to this factor.

The flotation process does not require a separate flocculation unit, and this has definite advantages. It has been shown that it is best to add alum at the point of pressure release where mixing occurs so that the chemicals are well dispersed. Brown and Caldwell (1976) designed two tertiary treatment plants that employ flotation and developed design considerations to be applied when employing flotation. These features are not included in standard flotation units and should be incorporated to ensure good algae removal (Parker, 1976).

In addition to incorporating various mechanical improvements, Brown and Caldwell recommended that the tank surface be protected from excessive wind currents to prevent float movement to one side of the tank. It was also recommended that the flotation tank be covered in rainy climates to prevent the breakdown of floc. Another proposed alternative is to store the wastewater in treatment ponds during the rainy season and then operate the flotation process at a higher rate during dry weather.

Dissolved air flotation thickening (DAFT) has been used at the Stockton, California, regional wastewater treatment facility for many years to remove algae from the treatment ponds ahead of the tertiary filtration process. Performance results for the period from June to October 2005 showed an average pond influent TSS concentration of 74 mg/L (range, 20 to 223). Effluent concentrations averaged 34 mg/L (range, 15 to 105). The percentage removal averaged 50%. In 2009–2010, the DAFT process tanks and internal equipment underwent major removal of floating algae, and the initial results indicate improved performance. The DAFT influent is secondary effluent that has received further treatment in facultative ponds and then flows through constructed wetlands put into service in 2007. Alum is fed to the DAFT influent for chemical conditioning of the algae solids. Performance results available for 2010 show that the influent TSS concentrations averaged 70 mg/L and effluent TSS concentrations averaged 17 mg/L, for an average removal efficiency of 76% (USEPA, 2011).

Alum–algae sludge was returned to the wastewater treatment ponds for over three years at Sunnyvale, California, with no apparent detrimental effect (USEPA, 2011). No sludge banks, floating mats of material, or increased TSS concentrations in the pond effluent have been observed. Returning the float to the pond system is

an operational option, at least for a few years. Most estimates of a period of time that sludge can be returned range from 10 to 20 years. Sludge disposal from a dissolved air flotation system can present considerable challenges. Alum–algae sludge is very difficult to dewater and discard. Centrifugation and vacuum filtration of raw alum–algae sludge have produced marginal results. Indications are that lime coagulation may prove to be as effective as alum to produce sludge that is more easily dewatered.

Brown and Caldwell (1976) evaluated heat treatment of alum–algae sludges using the Porteous, Zimpro® low-oxidation, and Zimpro® high-oxidation processes without great effects. The Purifa process, using chlorine to stabilize the sludge, produced a sludge that was dewaterable on sand beds or in a pond. If algae are killed before entering an anaerobic digester, the proportion of volatile matter destruction and dewatering can provide more useful results. But, as with the other sludge treatment and disposal processes, additional operations and costs are incurred, which may make the option of dissolved air flotation less competitive financially.

9.3 OPERATIONAL MODIFICATIONS AND ADDITIONS

9.3.1 AUTOFLOCCULATION AND PHASE ISOLATION

Autoflocculation of algae (natural settling under specific environmental conditions) has been observed in some studies (Golueke and Oswald, 1965; Hill et al., 1977; McGriff and McKinney, 1971; McKinney, 1977). *Chlorella* (single-cell green algae) was the predominant alga occurring in most of the cultures. Laboratory-scale continuous experiments with mixtures of activated sludge and algae have produced large bacteria–algae flocs with good settling characteristics (Hill and Shindala, 1977; Hill et al., 1977). Floating algal blankets have been reported in the presence of chemical coagulants in some cases (Shindala and Stewart, 1971; van Vuuren and van Duuren, 1965). This may be caused by the entrapment of gas bubbles produced during metabolism or by the fact that, at a particular stage in the growth cycle, algae have neutral buoyancy. In an 113,355-L/hr (3000 g/hr) pilot plant that combined flocculation and sedimentation, a floating algal blanket was formed with alum dose of 125 to 170 mg/L. About 50% of the algae was able to be skimmed from the surface (van Vuuren and van Duuren, 1965). Given the unpredictable occurrence of conditions necessary for autoflocculation, it cannot be considered a reliable method for removing algae from wastewater treatment ponds.

Phase isolation is defined as the operation of a pond system to create natural conditions favorable to settling of algae, and some success has been reported based on this phenomenon to remove algae from pond effluents. The results of a study by McGriff (1981) of full-scale operation of a phase isolation system were not consistent. Oswald and Green (2000) enhanced algal growth in a high-rate pond with a raceway configuration and a slow-moving paddle wheel to keep algae suspended. This concentrated algal slurry is sent to a settling basin, where the algae can be concentrated further and sent to a drying bed. There is a potential to use the algal slurry for feed supplement, soil fertilization and amendment, and, most recently, for biofuel production (Brune et al., 2009; Woertz et al., 2009).

9.3.2 BAFFLES AND ATTACHED GROWTH

Enhancement of attached microbial growth in oxidation ponds is an apparently practical solution for maintaining a biological population while still obtaining the treatment desired. Although baffles are considered useful primarily to ensure good mixing and to eliminate the problem of short-circuiting, they provide a substrate for bacteria, algae, and other microorganisms to grow (Polprasert and Agarwalla, 1995; Reynolds et al., 1975). In general, attached growth surpasses suspended growth if sufficient surface area is available. In anaerobic or facultative ponds with baffling or biological disks, the microbiological community consists of a gradient of algae to photosynthetic, chromogenic (produces characteristic color or pigment) bacteria and, finally to nonphotosynthetic, nonchromogenic bacteria (Reynolds et al., 1975). In these experiments, the microbial growth associated with the baffled system was identified as the mechanism that produced a more effective treatment. Simple fixed baffles constructed of wood or plastic, floating plastic baffles used to improve hydraulic characteristics, or, indeed, any surface can provide a substrate on which microbial growth can take place. Polprasert and Agarwalla (1995) demonstrated the significance of biofilm biomass growing on the side walls and bottoms of ponds and presented a model for substrate utilization in facultative ponds using first-order reactions for both suspended and biofilm biomass.

9.3.3 LAND APPLICATION

Land application of wastewater for treatment (effluent polishing) is defined as the application of appropriately pretreated municipal and industrial wastewater to the land at a controlled rate in a designed and engineered setting. The purpose of the activity is to obtain beneficial use of these materials, to improve environmental quality, and to achieve treatment goals in a cost-effective and environmentally sound manner. In many cases, the production and sale of crops can partially offset the costs of treatment. In arid climates, the practice allows the use of wastewaters for irrigation and preserves higher quality water sources for other purposes. The design and operation of land treatment systems is described in detail in Reed et al. (1995), Crites et al. (2000), and USEPA (2006). These publications should be consulted before designing a land application system to polish a pond effluent. Ecological conditions will dictate whether this is an option that should be considered.

9.3.4 MACROPHYTE AND ANIMAL SYSTEMS

Various macrophytic floating plants (i.e., aquatic plants that grow in or near water and are emergent, submergent, or floating) have been used to reduce algal concentrations and TSS in maturation ponds (Rittman and McCarty, 2001). Note that the macrophyte population in a water body may indicate water quality problems. A decline in a macrophyte population may indicate excessive turbidity, herbicides, or salinization. Conversely, overly high nutrients levels may create an overabundance of macrophytes, which may interfere with natural processes (Spellman, 2013). Detailed design information can be obtained in Reed et al. (1995), Pearson and Green (1995), Mara et al. (1996), Pearson et al. (2000), and Shilton (2005).

9.3.4.1 Floating Plants

Although a number of aquatic macrophytes, including alligator weed (*Alternanthera philoxeroides*), duckweed (*Lemna* spp.), pennywort (*Centella asiatica*), water ferns (*Azolla* spp.), water hyacinths (*Eichhornia crassipes*), and submerged vascular plants appear to offer the greatest potential for wastewater treatment in general, by far the greatest emphasis has been placed on the utilization of water hyacinths. A native of South America, water hyacinth was introduced into the United States in 1884, where it spread rapidly and became established in the waterways of several southern states. Due to rapid growth, problems such as obstruction of water flow and water loss through transpiration resulted. Weed control programs were initiated in 1899; early control measures involved mechanical procedures which were later replaced by the use of herbicide. Holm et al. (1969) estimated a loss of \$43 million in the southeastern United States during 1956 despite extensive control efforts.

Water hyacinths are widely distributed in the tropical and subtropical regions of the world. Generally, the geographical area in which water hyacinths thrive is bounded by 32°N and 32°S latitude. The number of water hyacinth plants, among the fastest growing of aquatic macrophytes, doubles every 10 to 15 days under favorable conditions. Penfound and Earle (1948) reported water hyacinth mats having densities of 125 to 184 tons per acre. Growth studies reported by Wolverton and McDonald (1976a) indicated that 1 acre can produce 800 to 1600 pounds of water hyacinth per day.

Wastewater treatment systems utilizing water hyacinths are designed to remove or degrade nutrients, organic material, trace metals, solids, and microorganisms. Reed et al. (1995) and Robinson et al. (1976) presented detailed design considerations with respect to hyacinth growth rates, degrees of nutrient removal required, and the use of these plants to improve wastewater quality for reuse. For tertiary treatment, Robinson et al. (1976) estimated that 31 to 156 acres would be required for a throughput of 1 MGD at an annual production rate of 20 tons/acre. Participants of an EPCOT technology meeting at Walt Disney World in Florida (WED Enterprises, 1976) concluded that about 15 acres of water hyacinths could process 1 MGD of municipal wastewater. A plan was developed to design a water hyacinth system for the tertiary treatment of sewage coupled with the production of useful products from the biomass. A variety of uses have been evaluated for harvested water hyacinths, including animal feed, compost, fertilizer, paper products, conversion to methane, and alcohol production. Based on a study to evaluate the economics and processing of water hyacinth products for cattle feeding, paper-making, and compost, Bagnell et al. (1974) suggested that compost may be the best use, as this product had the highest value with the lowest processing cost. In tests involving anaerobic fermentation of water hyacinth, Wolverton et al. (1975) found that the biogas produced contained a high percentage of methane. At an incubation temperature of 36°C, non-contaminated plants yielded 8.9 mL methane per gram wet weight, while nickel-cadmium-contaminated plants yielded 11.3 mL methane per gram wet weight. Methane content of the total biogas produced was 69.7% and 91.1%, respectively.

In the study of a drainage canal receiving municipal effluent from the Gregory, Texas, wastewater treatment plant, Dinges (1976a) observed a mean reduction in BOD₅ of 35.6%. The canal surface area was 1.2 acres with a throughput of 140,000

gallons per day. Dinges (1976b) found that the mean BOD and chemical oxygen demand (COD) decreased dramatically through a pilot system composed primarily of water hyacinth pond units receiving stabilization pond effluent from the Williamson Creek Wastewater Treatment Plant at Austin, Texas. The pilot system, occupying a surface area of 0.14 acres with a detention time of about 5 days, yielded mean reductions in BOD₅ from 19 mg/L to 3.5 mg/L, BOD₁₀ from 108 mg/L to 20 mg/L, soluble BOD₅ from 8.1 mg/L to 2.2 mg/L, COD from 82 mg/L to 32 mg/L, soluble COD from 55 mg/L to 30 mg/L, and total organic carbon (TOC) from 15.3 mg/L to 9.8 mg/L.

In laboratory-scale investigations Wolverton et al. (1975) found that the BOD₅ of raw sewage was reduced 97% by utilizing water hyacinths compared to 61% for the plant-free control, and the BOD₅ of secondary effluent was reduced 77% compared with 6% for the control following 7 days of exposure. An experimental hyacinth lagoon at Orange Grove, Mississippi, studied by Wolverton and McDonald (1976b,c) for a period of a year, showed a reduction in BOD₅ for varied rates of flow. The hyacinth lagoon, which received effluent from an aerated primary and secondary lagoon series, had a surface area of 0.28 hectares and a volume of 6.8 million liters. During 2 months of operation at a flow of 437,000 L/day, a BOD₅ reduction of 75% and a TOC reduction of 31% were noted. Operation for 4 months at 870,000 L/day resulted in a 79% reduction of BOD₅ and a 26% reduction of TOC. Four months at 1,059,000 L/day resulted in a 66% reduction in BOD₅ and a 25% reduction in TOC. Reductions in BOD₅ of 60% and TOC of 34% were noted for 2 months of operation at a flow of 1,892,500 L/day.

Wolverton and McDonald (1976c, 1975) evaluated a single-cell sewage lagoon located at Bay St. Louis, Mississippi, in terms of utilizing water hyacinth to upgrade the effluent. The lagoon had a surface area of 17.5 hectares and a domestic wastewater influent of about 3.8 million L/day. An enclosed area of 2.5 hectares around the point of discharge contained water hyacinth. Over a 4-month period, a 60% reduction in BOD₅ occurred, from 39 mg/L to 16 mg/L.

9.3.4.2 Submerged Plants

Submerged aquatic macrophytes for treatment of wastewaters have been studied extensively in the laboratory, in greenhouses, in a pilot study by McNabb (1976), and in large-scale wetland stormwater treatment systems designed to remove phosphorus to less than 20 mg/L (USEPA, 2011).

9.3.4.3 *Daphnia* and Brine Shrimp

Pennak (1989) observed that, “because of their interesting habits, their availability in nearly all types of fresh-water habitats, and their complex but easily studied anatomy, the [*Daphnia* spp.] water fleas have been favorite subjects of observation ... even since the invention of the microscope” (p. 369). *Daphnia* spp. are filter feeders, and their main contribution to wastewater treatment is the removal of suspended solids, particularly algae (USEPA, 2002). *D. magna* (see Figure 9.5) is principally a lake dweller that is restricted to waters in northern and western North America exceeding a hardness of 150 mg/L as CaCO₃ (Pennak, 1989). In the Netherlands, *D. magna* are found in shallow ponds with muddy bottoms rich in organic matter and

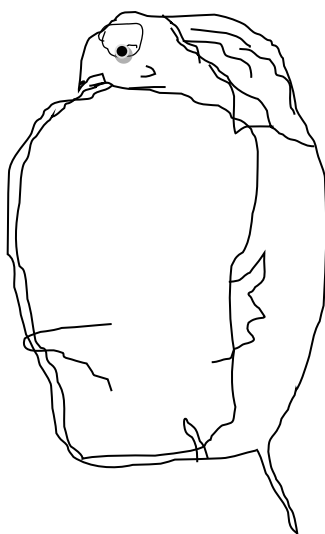


FIGURE 9.5 Lateral aspect view of *Daphnia magna*.

with low oxygen demand (3 to 4 mg/L). *D. pulex* is principally a pond dweller where the oxygen content is higher, but is also found in lakes. It is generally considered a clean water species that is dominant in nature during periods of low turbidity. However, Scholtz et al. (1988) found that high turbidity had little effect on survival and reproduction in laboratory studies.

The taxonomic status of *Artemia* has long been controversial because there is considerable morphological variability over parts of its range. The current consensus is that there is a single cosmopolitan species, *Artemia salina*, which has numerous intergrading physiological and morphological varieties (Pennak, 1989). Brine shrimp belong to the subclass Branchiopoda, which is characterized by many pairs of flattened appendages on the thorax, in contrast to other members of the Crustacea that have no more than six pairs. Probably the distinctive feature of *Artemia salina* is the compressed, triangular, and blade-shaped distal segment of the second antenna of the male. The mature adult is 8 to 10 mm long with a stalked lateral eye, sensorial antennulae, a linear digestive tract, and 11 pairs of thoracopods. In the male, the antennae are transformed into muscular claspers used to secure the female during copulation.

9.3.4.3.1 *Daphnia*

Daphnia populations are generally sparse in winter and early spring, but as water temperatures reach 6 to 12°C, they increase in abundance and subsequently may reach population densities as high as 200 to 500 individuals per liter (Pennak, 1989). Populations in ponds decline to very low numbers during the summer months. In autumn, there may be a second population pulse, followed by a decline to winter lows. During most of the year, populations of *Daphnia* consist almost entirely of females, the males being abundant only in spring or autumn when up to 56% of the

offspring of *D. magna* may be males (Barker and Hebert, 1986). Males are distinguished from females by their smaller size, larger antennules, modified postabdomen, and first legs, which are armed with a stout hook used in clasping. Production of males appears to be induced principally by low temperatures or high densities and subsequent accumulation of excretory products and a decrease in available food. These conditions may induce the appearance of sexual (resting) eggs (embryos) in cases called ephippia, which are cast off during the next molt. It appears that the shift toward male and sexual egg production is related to the metabolic rate of the parent. Any factor that tends to lower metabolism may be responsible. Ruvinsky et al. (1978) suggested that the genome of the animal has two developmental programs based on identical sets of chromosomes. The female program consistently functions under a wide range of conditions, whereas the male program is turned on by specific ecological stimuli. The eggs from which the males and females develop have identical chromosome sets. Sex determination is based on changes in chromatin structure when the mother receives a specific signal that sexual reproduction is needed for adaptation to extreme conditions.

Daphnia magna reproduce only by cyclic parthenogenesis in which males contribute to the genetic makeup of the young during the sexual stage of reproduction, whereas *D. pulex* may reproduce by either cyclic or obligate parthenogenesis in which the zygotes develop within the ephippium by ameiotic parthenogenesis with no genetic contribution for the males. Thus, the ephippial and live-born offspring are genetically identical to their mothers. Both forms may be present in the same population, resulting in cyclic populations exhibiting considerable genetic variation early in the year and an obligate population with a low range of genotypic values. After 25 generations of asexual reproduction, the variation in the cyclic parthenogenesis group becomes about the same as that in the obligate group (Lynch, 1984). Populations exhibiting a low range of genotypic values are much more vulnerable to perturbations such as nutrient introduction or toxic discharges. The clonal makeup of a *Daphnia* population is affected by food, oxygen, temperature, and predation (Brookfield, 1984; Weider, 1985).

Ephippia are small and lightweight and can be dried and stored for long periods, making them easy to transport. They may be shipped in envelopes like seeds. Upon arrival at the new location the ephippia can be hatched in a few days when placed in water at the proper temperature (Schwartz and Hebert, 1984).

Daphnia are preyed upon by many predators and have developed behavioral and morphological antipredator defenses to make themselves more difficult to catch and consume. Dodson (1988) showed that *D. pulex* responded to possible chemical stimuli released by a predator which resulted in the daphnids retreating from the vicinity of the predators. Certain clones of *D. pulex* may develop morphological changes when predators are present but not when they are absent from the pond. Some of these changes are of such magnitude that they have been described as separate species. *D. minnehaha* is a morphological variation of *D. pulex* that develops spines in response to the stimuli of predators (Krueger and Dodson, 1981). Different genotypes of *D. pulex* react in different ways to the predator (*Chaoborus*) factor and to temperature (Havel, 1985).

Both *Daphnia pulex* and *D. magna* are well adapted to live in algal blooms, which are high in proteins and carbohydrates, where they feed on algae and bacteria. *D. magna* prefers bacteria to algae as food (Ganf, 1983; Hadas et al., 1983), while *D. pulex* uses bacteria as food only when algal biomass declines (Borsheim and Olsen, 1984). Food type and abundance affect the sensitivity of *Daphnia* to pollutants and their reproduction rate. Keating and Dagbusan (1986) showed that both *D. pulex* and *D. magna* diatoms were more tolerant of pollutants than those fed only green algae. Lipid reserves are a good indication of the nutritional condition of the animals (Holm and Shapiro, 1984; Tessier and Goulden, 1982).

Four distinct periods may be recognized in the life history of *Daphnia*: (1) egg, (2) juvenile, (3) adolescence, and (4) adult (Pennak, 1989). The life span of *Daphnia*, from the release of the egg into the brood chamber until the death of the adult, is highly variable depending on the species and environmental conditions (Pennak, 1989). Generally, the life span increases as temperature decreases, due to lowered metabolic activity. The average life span of *D. magna* is about 40 days at 25°C and about 56 days at 20°C. The average life span of *D. pulex* at 20°C is approximately 50 days. Typically, a clutch of 6 to 10 eggs is released into the brood chamber, but as many as 57 have been reported. The eggs hatch in the brood chamber and the juveniles, which are already similar in form to the adults, are released in approximately 2 days when the female molts (casts off her exoskeleton or carapace). The time required to reach maturity (produce their first offspring) in *D. pulex* varies from 6 to 10 days (mean, 7.78 days) and also appears to be dependent on body size. The growth rate of the organism is greatest during its juvenile states (early instars), and the body size may double during each of these stages. *D. pulex* has three to four juvenile instars, where *D. magna* has three to five instars. Each instar stage is terminated by a molt. Growth occurs immediately after each molt while the new carapace is still elastic.

Following the juvenile stages, the adolescent period is very short and consists of a single instar. It is during the adolescent instar that the first clutch of eggs reaches full development in the ovary. Generally, eggs are deposited in the brood chamber within minutes after molting, and the young that develop are released just before the next molt.

Daphnia magna usually has 6 to 22 adult instars, and *D. pulex* has 18 to 25. In general, the duration of instars increases with age but also depends on environmental conditions. A given instar generally lasts approximately 2 days under favorable conditions, but when conditions are unfavorable it may last as long as a week.

Four events occur in a matter of a few minutes at the end of each adult instar: (1) release of young from the brood chamber to the outside, (2) molting, (3) increase in size, and (4) release of a new clutch of eggs into the brood chamber. The number of young per brood is highly variable for *Daphnia*, depending primarily on food availability and environmental conditions. *D. magna* and *D. pulex* may produce as many as 30 young during each adult instar, but more commonly the number is 6 to 10. The number of young released during the adult instars of *D. pulex* reaches a maximum at the tenth instar, after which there is gradual decrease (Anderson and Zupancic, 1937). Scholtz et al. (1988) reported that nearly all of the eggs that are oviposited by *D. pulex* became neonates, indicating a highly successful hatching rate. The maximum number of young produced by *D. magna* occurs at the fifth adult instar, after which it decreases.

With regard to environmental conditions affecting the growth and lifespan of *Daphnia* spp., *Daphnia* is sensitive to the wastewater concentration of NH_3 , which is toxic to invertebrates. To be effective, shading (discussed later) is required to prevent the growth of algae that will result in high pH values during the daytime. The addition of acid and gentle aeration may be necessary (USEPA, 2002).

9.3.4.3.2 Brine Shrimp

Artemia are found nearly worldwide in saline lakes and pools. In North America, they have been reported throughout the western United States, in Nebraska and Connecticut, and in Saskatchewan, Canada. They are probably more widely distributed than indicated because of the limited efforts in many areas of the country to collect them. They are absent from many suitable habitats, probably because of their limited dispersal methods (USEPA, 2002). The ecological conditions under which brine shrimp live are highly variable. The salinity can exceed 300‰, where most other life cannot survive. Favored by the absence of predators and food competitors in such places, *Artemia* develop very dense populations. Although not a marine species, they sometimes occur in bays and lagoons where brines are formed by evaporation of seawater (salt pans). They are more commonly found in highly saline lakes, such as the great Salt Lake, where the shoreline may become ringed with brown layers of accumulated brine shrimp cysts. Brine shrimp are also common in evaporation basins used for the commercial production of salt.

The reproductive habits of different populations vary considerably. In parts of Europe parthenogenesis is the rule, males being rare or absent, but in North America most *Artemia* populations seem to be diploid with males common. The principal mechanism of *Artemia* dispersion is transportation of the cysts by wind or waterfowl and by deliberate or accidental human inoculation. Growth of brine shrimp is influenced by many factors, and the tolerance of these factors is strain dependent. Optimum temperature for most strains ranges between 25 and 35°C, but strains have been reported thriving at 40°C. Most geographical strains do not survive temperatures below 6°C except as cysts. These cysts are tolerant of temperatures from far below 0°C to near the boiling point of water. Although *Artemia* can survive and reproduce under a wide range of salinity, they are seldom found in nature in salinities below 45‰ or above 200‰. The pH tolerance of *Artemia* varies from neutral to highly alkaline but the cysts will hatch best at a pH of 8 or higher. Many predators including many zooplankton that populate natural saltwaters, many saltwater fish, several insect groups (odonates, hemipterans, and beetles), and birds feed on brine shrimp in situations where they can tolerate the conditions.

Brine shrimp are typically filter-feeders that consume organic detritus, microscopic algae, and bacteria. Blooms of microscopic algae are favorite habitats of *Artemia*, and large populations develop in such areas where they feed on the algae and heterotrophic bacteria that are produced by these blooms. Brine shrimp populations have done well in cultures when fed algae, rice bran (Sorgeloos et al., 1979), soybean meal, or whey powder (Bossuyt and Sorgeloos, 1979). The nauplii do not need food for 4 days after hatching. Most strains of *Artemia* produce cysts that float (cyst from the Mono Lake, California, strain sink). These cysts remain in diapause as long as they are kept dry or under anaerobic conditions. Upon hydration,

the embryo in the cyst becomes activated. After several hours, the outer membrane bursts and the embryo emerges still encased in the hatching membrane. Soon the hatching membrane is ruptured and the free-swimming nauplius is born. The first instar grows through about 15 molts and becomes differentiated into male or female after the tenth molt. Copulation is initiated when the male grasps the female with its modified antennae. The fertilized eggs either develop into free-swimming nauplii or are surrounded by a thick shell and deposited as cysts which are in diapause.

9.3.4.4 Fish

Fish have been grown in treated wastewaters for centuries, and, where toxics are not encountered, the process has been successful. Many species of fish have been used in wastewater treatment, but fish activity is temperature dependent. Most grow successfully in warm water. Catfish and minnows are exceptions. Dissolved oxygen concentrations are critical and the presence of NH_3 is toxic to the young of the species. Detailed studies of fish in wastewater treatment ponds were conducted by Coleman (1974) and Henderson (1979). Numerous studies of fish culture have been conducted around the world. Polprasert and Koottatep (2005) presented an excellent summary of the use of algae-eating fish in pond systems.

9.4 CONTROL OF ALGAE AND DESIGN OF SETTLING BASINS

Control of algae in wastewater treatment pond effluents has been a major concern throughout the history of the use of these systems. Algae grow in maturation and polishing ponds following all types of treatment processes, which increases the TSS in the effluent. State design standards requiring long detention times in the final cell in a pond system have inadvertently exacerbated the problem. In recognition of the difference between the source of the TSS in the influent and the effluent, the state of Minnesota has mandated a higher TSS limit of 45 mg/L for ponds (USEPA, 2011).

It has been established that few, if any, of the solids in pond effluents are fecal matter or material entering the pond system. This has led to much discussion about the necessity of removing algae from pond effluents. Although the concern that the TSS might harbor human pathogens may not be realistic, when the algae die, settle out, and decay they do create some O_2 demand on the receiving stream. The concern about decay and O_2 consumption has led to investigations of the most effective methods to remove algae and how to design systems to minimize growth in the settling basins. Toms et al. (1975) studied algal growth rates in polishing ponds receiving activated sludge effluents for 18 months. They concluded that growth rates for the dominant species were less than 0.48/day, and if the hydraulic retention time (HRT) was less than 2 days then algal growth would not be a problem. At an HRT of less than 2.5 days, the effluent TSS decrease. Uhlmann (1971) reported no algal growth in hyperfertilized ponds when the detention times were less than 2.5 days. Toms et al. (1975) evaluated one- and four-cell polishing ponds and found that for HRTs beyond 2.5 days the TSS increased in both ponds, but significant growth did not occur until after 4 to 5 days in the four-cell pond.

Algae require light to grow, and as light penetration is reduced with increasing depth it might be hypothesized that increasing the depth of a maturation or polishing pond would help to reduce algal growth. As most pond cells are trapezoidal, there is little to be gained by increasing the depth beyond 3 to 4 meters. Without mechanical mixing, thermal stratification occurs in ponds, providing an excellent environment for algae to grow. Disturbing stratification will reduce algal growth. Rich (1999) recommended some degree of aeration for pond cells to control algae. The higher aeration rate will suspend more solids. The resulting reduction in light transmission helps to reduce the rate of algal growth.

9.4.1 CONTROL OF ALGAL GROWTH BY SHADING, BARLEY STRAW, AND ULTRASOUND

9.4.1.1 Dyes

Dyes have been applied to small ponds to control algal growth; however, the USEPA has not approved dyes for use in municipal or industrial wastewater ponds. Aquashade®, a mixture of blue and yellow dyes, is marketed as a means of controlling algae in backyard garden pools and large business park and residential development ponds. The product is registered with the USEPA for these uses.

9.4.1.2 Fabric Structures

Operators of ponds in Colorado and other locations have constructed structures suspending opaque greenhouse fabrics to reduce or eliminate light transmittance in small wastewater ponds. The screening has been successful, but in some cases fabrics were not fastened adequately, and they were damaged by the wind. Covering the final pond with adequate protection from the wind should reduce or eliminate algal growth. With full coverage of the surface, anaerobic conditions may develop and aeration of the effluent may be necessary to meet discharge standards. Partial shading in the correct proportions should reduce the possibility of creating anaerobic conditions.

9.4.1.3 Barley Straw

In 1980, it was observed that the addition of barley straw to a lake reduced the algal concentration. Placing barley straw in ponds has been proposed as a means of controlling algal growth. Details for the application of barley straw are given in Newman (1999). During decomposition, the chemicals listed in Table 9.12 are released to the water and inhibit the growth of algae (Everall and Lees, 1997). The acceptability of this method of algal control by regulatory agencies has not been resolved.

*9.4.1.3.1 Using Barley Straw**

Question: If you are not Anheuser Busch, what does one do with barley?

* Adapted from Corley, C., Barley straw works wonders on suspended algae solids, *Environmental Progress*, 28(1), 8–9, 2003; USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, EPA/600/R-11/088, U.S. Environmental Protection Agency, Washington, DC, 2011.

TABLE 9.12
List of Some Chemicals Produced by
Decomposing Straw

Acetic acid
Deconoic acid
Dodecanoic acid
Hexadecanoic acid
Hexanoic acid
Nonanoic acid
Octanoic acid
Tetradecanoic acid
1-Hexacosene
1-Methylnaphthalene
1,1,4,4-Tetramethyl-2,6-bis(methylene) cyclohexone
2-(1,1-Dimethylethyl phenol)
2-Methylbutanoic acid
2,6-Dimethoxy-4-(2-propenyl) phenol
2,3-Dihydrobenzofuron
3-Methylbutanoic acid
5,6,7,7A-Tetrahydro-4,4,7A-trimethyl-(4H) benzofuranone

Source: Adapted from Everall, N.C. and Lees, D.R.,
Water Res., 312, 614–620, 1997.

Answer: The days of filling a feedbag of a horse-drawn milk wagon being long gone, the sensible use is to float it, the straw portion at least, on your pond, ditch, impoundment, or reservoir. Why? Well, as some people have found from German Valley, Illinois, to Manchester, England, your water will be clearer, cleaner, and lower in suspended solids due to algae.

In the United Kingdom, the decomposition of barley straw and its effects on algae have been studied since the late 1980s by a number of researchers, including Dr. Jonathon Newman, University of Bristol, Department of Agricultural Sciences, Reading, U.K. The observations reported have identified rotting barley straw as an effective inhibitor of the color and suspended solids attributed to various types of algae. The research has been conducted in impoundments, slow-moving canals, and many other bodies of water, and the findings have been confirmed by laboratory studies. This has led researchers to suggest that, “Decomposing barley straw inhibits the growth of both filamentous and blue–green algae species in all types of water bodies so far assessed” (Newman and Barrett, 1993).

What causes barley to be so effective has not been truly identified. Again, researchers have analyzed the many chemical constituents produced by rotting barley straw (Newman, 1999), but no one chemical is predominant, and the combined effect appears to be the controlling factor. Not the presence of the straw but the decomposition products appear to provide the effect. Other straws and plant materials have

been tested and dismissed in preference to barley (Newman, 1999). For example, green plant material such as alfalfa and hay impart an organic load on the system, but wheat straw, corn, and lavender stalks, quite common Illinois plant materials, not quite as much, and they all seem to have poorer effects and longevity. Despite uncertainty regarding the exact mechanism that produces the benefit, a benefit it is, one that is easily measured and observed, at that.

Transferring the technology, if one can refer to rotting barley straw as technology, to wastewater systems at best would seem a stretch. Newman's own studies indicate that algae growth continues with sufficient nutrient concentrations (Newman, 1999). Further, although algae and fungi appear to be affected, all other aquatic animal and plant life is not, nor is dissolved oxygen. Therefore, no detrimental conditions would be expected and, if any benefit accrues in wastewater systems, all would be positive steps.

The application, of this truly natural and beneficial product, to water bodies of all types is fundamentally simple. Bundle it, float it, and watch it rot! No need to search for the "right" type or vintage of barley straw, if there is one. Find the nearest, cheapest, and most readily available source and have at it. A slight oversimplification perhaps, but the years of observation have demonstrated a few basics, all confirmed by trials in Illinois communities and industries.

The few basics that have been displayed during the use of barley in Illinois include these: First, the straw must be floating throughout the application period; when it is allowed to sink, the thought is that it becomes a detrimental organic load. Second, because the original uses were in surface water ponds and impoundments and not wastewater systems, repeated applications are necessary from spring through warm weather. Warm weather and wind action on the surface are two necessary ingredients. Also, keeping the straw loosely packed inside a long open-web material such as common snow fence is ideal and preferred to the more open-weave Christmas wrap where straws can escape.

Success can be found in all corners of Illinois. From Gardener to Ohio and Sorrento to Hudsonville, barley straw decomposition abounds. Measurable and observable benefits without any detrimental environmental effects abound. First used in Gardner at a wastewater pond system, it reduced the use of copper sulfate while improving the effluent suspended solids for weeks during the hottest part of the summer of 2000. The water plant operator at Sorrento experienced similar benefits during the summer of 2002 when lower turbidity was demonstrated and fewer applications of admittedly useful but potentially hazardous copper sulfate were needed. Other wastewater applications include ash pond treatment at the Amerens Hudsonville generating station, where the use of barley straw reduced the algae count in the effluent along with the suspended solids while positively affecting the pH of the discharge to the Wabash River. Use of barley straw at Ohio was initiated late in the summer of 2001. Although a huge margin of success was not expected because of sludge pockets in all pond cells, the floating barley straw booms were effective in keeping the effluent suspended solids from exceeding the permitted limits for weeks.

Following is a list of materials and their cost (an application rate of 20 g/m² straw is the same as 1 oz./yd²):

- Four to five 45-pound bales of barley straw for each acre @ \$5 to \$35
- Two 100-ft rolls of snow fence @ \$20
- Two rolls 350-lb test polyethylene rope @ <\$10
- Two fence posts @ \$1.89
- Sixty 1-gallon and 1/2-gallon bottles
- One tube silicon sealant @ \$2.95
- Nylon zip ties @ lowest cost
- Two and a half hours on a sunny day.

Following is a summary of the method:

- *Flotation*—Both gallon and half gallon bottles spaced 5 feet apart
- *Sealant*—Silicon seal the inside of bottle caps
- *Configuration*—Sausage boom
- *Size*—Two @ 95 ft in series or parallel (or divide length as needed)
- *Location*—Diagonally upwind, in mixing pattern
- *Anchor*—Double strands of poly rope tied to posts.

Documentation includes the following:

- Determine BOD and TSS loading on all cells and compare to the design.
- Sample in early spring, before algae bloom starts or before first application.
- Sample treated cell influent and effluent TSS weekly.
- Compare results to the same times in previous years.

9.4.1.4 Ultrasound

Ultrasound devices have been used for algal control in golf course ponds, large residential area ponds, and water treatment storage ponds, but limited data are available for municipal pond systems. A microcosm study at the Centre for Aquatic Plant Management (CAPM) evaluated the efficacy of several treatment options to control algae (Clarke, 2004). Methods included an ultrasonic device, a recirculating pump, bacteria, barley straw, Aquavantage (electromagnet treatment), EcoFlo (fixed magnet), and a control. None of the treatments appeared to remove the algae to a level that would meet water quality requirements. Differences in the level of algae could be seen, but some of the four replicate tanks in all treatments remained turbid and green. The only tanks that were clear were found to be populated by *Daphnia* spp., an invertebrate herbivore. Clarke reported that no significant differences could be found between treatments. The variability and experimental challenges made it difficult to draw conclusions as to the possible causes of either growth or inhibition of growth. The CAPM investigated the mode of action of ultrasound on algae and found that *Spirogyra* and *Selenastrum* were damaged irreversibly by the treatment (Clarke, 2004).

9.5 COMPARISON OF VARIOUS DESIGN PROCEDURES

The variety of configurations and objectives of the design approaches for nutrient removal makes it difficult to make direct comparisons to determine which will be the most effective for a given site. Reasonable 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 successful pond performance, barring any toxic effects. The importance of the hydraulic design of a pond system to achieve water quality objectives cannot be overemphasized.

9.6 OPERATIONAL MODIFICATIONS TO FACULTATIVE PONDS

9.6.1 CONTROLLED-DISCHARGE PONDS

No rational or empirical design model exists specifically for the design of controlled-discharge wastewater ponds. The unique features of controlled-discharge ponds are long-term retention and periodic, controlled discharge usually once or twice a year. Rational and empirical design models applied to facultative pond design may also be applied to the design of controlled-discharge ponds, provided allowance is made for the required larger storage volumes. Application of the ideal plug flow model developed for facultative ponds can be applied to controlled-discharge ponds if HRTs of less than 120 days are considered. A study of 49 controlled-discharge ponds in Michigan indicated that discharge periods vary from less than 5 days to more than 31 days, and residence times were 120 days or greater (Pierce, 1974). Ponds of this type have operated satisfactorily in the northcentral United States using the following design criteria:

- *Overall organic loading*—22 to 28 kg BOD₅/ha/day (20 to 25 lb BOD₅/ac/day)
- *Liquid depth*—Not more than 2 m (6 ft) for the first cell, and not more than 2.5 m (8 ft) for subsequent cells
- *Hydraulic detention*—At least 6 months of storage above the 0.6-m (2-ft) liquid level (including precipitation), but not less than the period of ice cover
- *Number of cells*—At least three for reliability, with piping flexibility for parallel or series operation

The design of the controlled-discharge pond must include an analysis showing that receiving stream water quality standards will be maintained during discharge intervals, and that the receiving watercourse can accommodate the discharge rates from the pond. The design must also include a recommended discharge schedule.

Selecting the optimum day and hour for release of the pond contents is critical to the success of this method. The operation and maintenance manual must include instructions on how to correlate pond discharge with effluent and stream quality. The pond contents and stream must be carefully monitored before and during the release of the pond contents.

In a typical program, discharge of effluents follows a consistent pattern for all ponds. The following steps are usually taken:

- Isolate the cell to be discharged, usually the final one in the series, by shutting off the valve on the inlet line from the preceding cell.
- Arrange to analyze samples for BOD₅, TSS, VSS, pH, and other parameters that may be required for a particular location.
- Plan work so as to be able to spend full time on control of the discharge throughout the period.
- Sample contents of the cell to be discharged for DO, noting turbidity, color, and any unusual conditions.
- Monitor conditions in the stream to receive the effluent.
- Notify the state regulatory agency of the results of these observations and plans for discharge, and obtain approval.
- If discharge is approved, commence discharge and continue as long as weather is favorable, DO is near or above saturation values, and turbidity is not excessive following the prearranged discharge flow pattern among the cells.
 - Draw down the last two cells in the series (if there are three or more) to about 46 to 60 cm (18 to 24 in.) after isolation, interrupting the discharge for a week or more to divert raw waste to a cell that has been drawn down and resting the initial cell before its discharge.
 - When the first cell is drawn down to about 60 cm (24 in.) in depth, resume the usual series flow pattern, without discharge.
 - During discharge to the receiving waters, samples should be taken at least three times each day near the discharge pipe for immediate DO analysis. Additional testing may be required for TSS.

Experience with these ponds is limited to northern states with seasonal and climatic influences on algal growth. The process will be quite effective for BOD₅ removal in any location and will also work with a more frequent discharge cycle than semiannually, depending on receiving water conditions and requirements. Operating the isolation cell on a fill-and-draw batch basis is similar to the “phase isolation” technique.

9.6.2 COMPLETE RETENTION PONDS

In areas of the United States where the moisture deficit (evaporation minus rainfall) exceeds 75 cm (30 in.) annually, a complete retention wastewater pond may prove to be the most economical method of disposal. Complete retention ponds must be sized to provide the necessary surface area to evaporate the total annual wastewater volume plus the precipitation that would fall on the pond. The system would be designed for the maximum wet year and minimum evaporation year of record if overflow is not permissible under any circumstances. Less-stringent design standards may be appropriate in situations where occasional overflow is acceptable or an alternative disposal area is available under emergency conditions. Monthly evaporation and precipitation rates must be known to properly size the system. Complete retention ponds

usually require large land areas, and these areas may not be productive once they have been committed to this type of system. Land for this system must be naturally flat or be shaped to provide ponds that are uniform in depth and have large surface areas. The design procedure for a complete retention wastewater pond system is presented in the following section.

9.6.2.1 Design Conditions for Complete Retention Ponds

Figure 9.6 presents data for estimating evaporation and precipitation in southern Arizona. The air temperature and wind speed data represent mean values over a 54- and 61-year period, respectively. The precipitation data are the mean of the 5 wettest

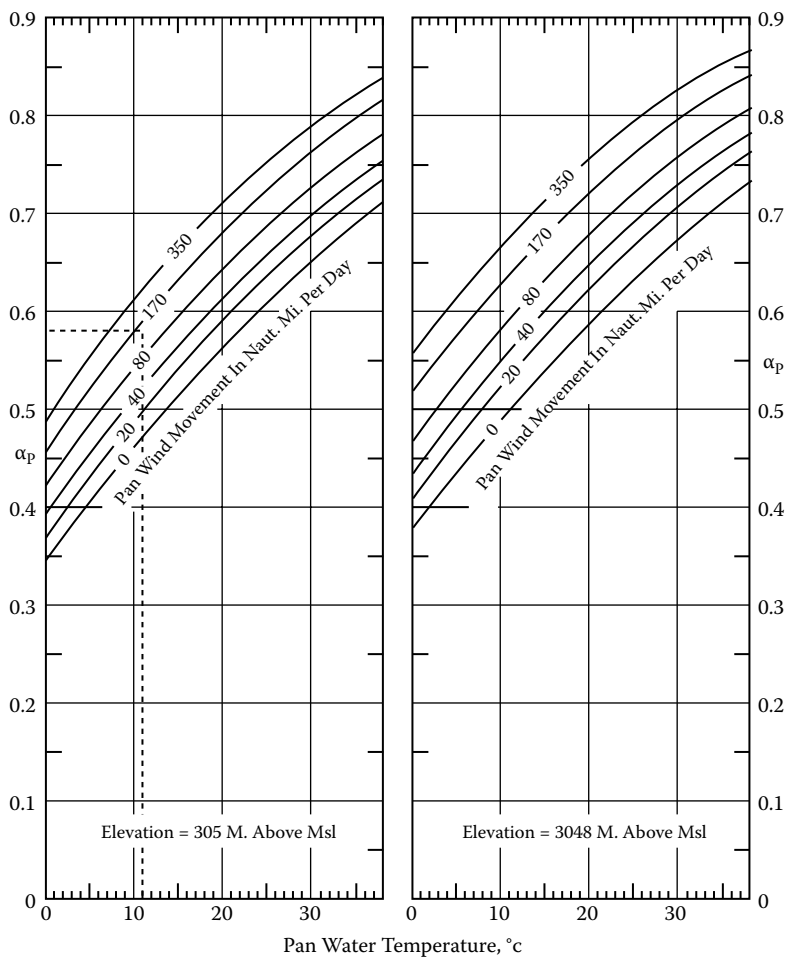


FIGURE 9.6 Proportion of advected energy (into a Class A pan) utilized for evaporation in metric units. (From USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.)

years over a 60-year period. The pan evaporation data represent the year with the lowest evaporation of a 10-year period. These values generally represent the worst case, thus providing for a conservative design. The difference between the surface water temperature and the air temperature is assumed to be 1°C . The selection of this value can have a significant effect on the evaporation losses as shown in Figure 9.7; therefore, the value must be selected to reflect local conditions:

- Surface water temperature (T_o) = air temperature (T_a) minus 1°C ; that is, $T_o - T_a = 1^{\circ}\text{C}$.
- $Q = 950 \text{ m}^3/\text{day}$ (0.25 MGD).
- Influent $\text{BOD}_5 = 150 \text{ mg/L}$.
- Seepage = 0.76 mm/day (0.2 in./wk).

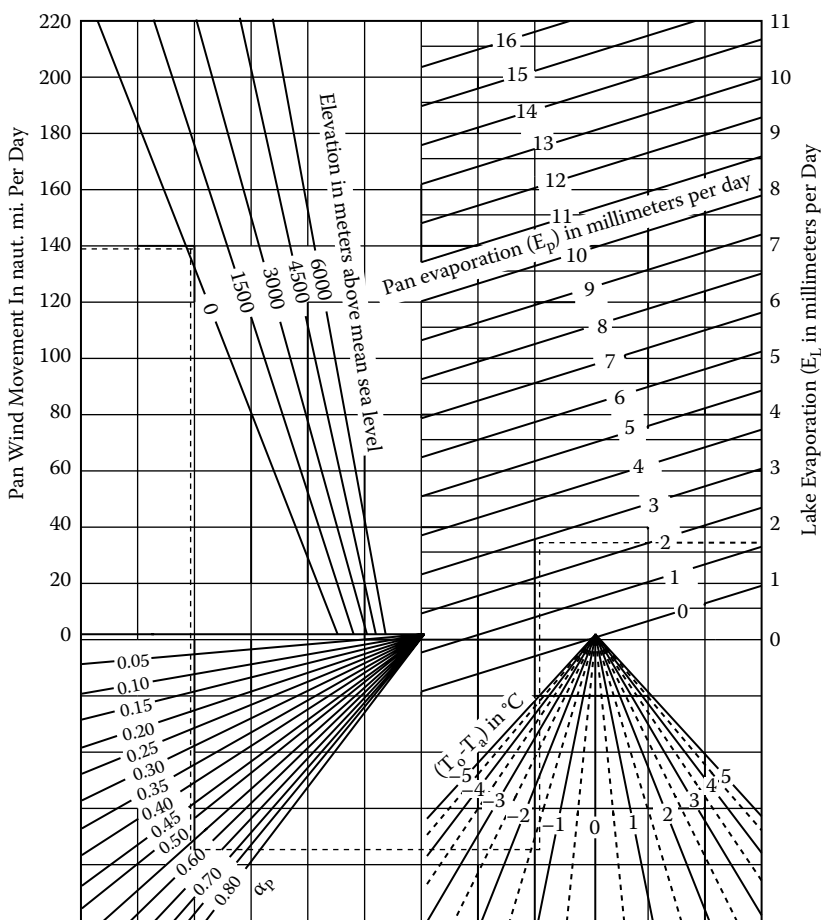


FIGURE 9.7 Shallow lake evaporation as a function of Class A pan evaporation and heat transfer through the pan in metric units per day. (From USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.)

Seepage is prohibited in some areas. State agency wastewater facility standards may require the pond bottom be sealed with an impervious line, reducing seepage to zero. Elevation is 300 m (980 ft) above mean sea level (MSL).

9.6.2.1.1 Requirements

Size a complete retention wastewater pond with no overflow for the given geographic area. Specify the following:

$$\text{Surface area } (A) = \frac{Q(365 \text{ days/yr})}{d - (\text{Annual precip.} - \text{Annual evap.} - \text{Annual seepage})}$$

where d is depth.

9.6.2.1.2 Solution

The design procedure consists of the following steps:

1. Using the data in Table 9.13 with Figure 9.6 (elevation = 305 m) and Figure 9.7, determine the mean monthly evaporation from the pond. The calculation for pond evaporation is shown on the figures by dashed lines. The results are presented in Table 9.14.
2. Using the data presented in Tables 9.13 and 9.14, calculate the area required for an assumed mean depth for one year of operation under design conditions. The mean depth (d) may range from 0.1 to 1.5 m (0.3 to 5.0 ft). The mean depth is usually near 1 m (3 ft).
3. Use the A value determined in step 2 to calculate the stage of the pond at the end of each month of operation during the design year.
4. Calculate the monthly stage of the pond under average conditions. If the pond is designed so that it never overflows, the average yearly evaporation and seepage must exceed the inflow and precipitation entering the pond.
5. Repeat steps 2 and 3 until a satisfactory pond depth is obtained.

Use $A = 142,259 \text{ m}^2$ (35 ac) to calculate the stage of the pond at the end of each month of operation. Table 9.14 contains a summary of the results of this procedure for the design year of operation, assuming the pond is empty at the beginning of the year.

An examination of the pond stage results in Table 9.15 shows that the maximum depth of water in the pond during the design year (conservative design data) would be 0.62 m (2 ft) plus the depth at the beginning of the design year. The pond stage under average conditions is shown in Table 9.16. Average evaporation and seepage are within 5% of inflow and precipitation. Assuming that several average years would occur in sequence, there would be a small accumulation of water in the pond. Because of the imprecise methods available to predict the sequence of occurrence of the design year and maximum and average years, the pond surface area of 142,259 m^2 is large enough to prevent overflow of the pond. The depth of complete retention ponds is limited only by groundwater conditions, evaporation rates, and cost. Generally, maximum depths range from 1 to 3 m (3 to 10 ft) with a freeboard of

TABLE 9.13
NOAA Climatological Data for Calculating Pond Evaporation and Precipitation

Month (Days in Month)	Mean Precipitation (mm/month)	Air Temperature (°C)	Wind (knots/day) ^a	Minimum 10-Year Pan		Mean
				Evaporation		10-Year Pan
				(mm/month)	(mm/day)	Evaporation (mm/month)
Jan (31)	12.3	12.4	140.4	87.5	2.82	105.0
Feb (28)	12.1	14.9	148.7	130.5	4.66	177.5
Mar (31)	10.1	17.7	154.2	198.2	6.39	220.0
Apr (30)	4.2	21.0	157.0	238.1	7.94	271.4
May (31)	2.9	24.6	154.2	332.0	10.71	365.2
June (30)	2.2	29.3	134.9	374.4	12.48	423.1
July (31)	6.8	32.8	140.4	416.0	13.42	449.3
Aug (31)	15.9	32.4	134.9	347.8	11.22	389.5
Sep (30)	10.6	29.1	115.6	278.5	9.28	323.1
Oct (31)	7.8	22.6	110.1	210.4	6.82	219.9
Nov (30)	8.3	16.8	126.6	137.4	4.58	163.6
Dec (31)	14.6	12.9	143.2	95.2	3.07	131.4
Total	107.8			2847.0		3238.9

Source: Adapted from USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

^a Knots are equal to the total of nautical miles per hour of wind per day.

0.6 m (2 ft). The maximum depth required will depend on the time of year that filling of the pond begins and the initial depth of water in the pond. It is not possible to predict accurately the water stage in the pond; therefore, it is necessary to exercise good judgment based on the constraints at particular locations. Estimates beyond the average- and design-year conditions can be made by analyzing historical data for the site, but this is still no guarantee of accuracy.

The water depth in the pond after one year of operation under design conditions will be equal to the mean depth plus the depth of water at the beginning of the year. During certain months of the year, the depth may exceed the mean depth when filling of the pond occurs at the beginning of the wet season. Three different starting dates are shown in Table 9.15 to illustrate this point. Using the above-mentioned procedure, it is possible for the design engineer to estimate the stage of the pond under as many conditions as considered necessary.

A maximum depth of 1.2 m (4 ft) would be adequate to avoid overflow from the pond by providing storage for 5 average years (Table 9.15) and a design year in sequence. It is unlikely that 5 average years of evaporation would precede the design year. The pond length (*L*) and width (*W*) values are calculated from the surface area (*A*). No restrictions are imposed on the length-to-width ratio. Also, the need to divide the pond volume to enhance hydraulic characteristics is eliminated. The most

TABLE 9.14
Calculated Pond Evaporation Data for Design and
Average Conditions

Month	αp	Design Pond Evaporation		Average Pond Evaporation
		(mm/day)	(mm/month)	(mm/month)
January	0.58	1.7	53	61
February	0.62	3.0	84	110
March	0.64	4.1	127	141
April	0.66	5.2	156	174
May	0.71	7.2	223	259
June	0.74	8.4	252	313
July	0.77	9.0	279	323
August	0.77	7.4	229	300
September	0.73	6.2	186	235
October	0.58	4.4	136	127
November	0.62	2.9	87	101
December	0.58	1.8	56	76
Total			1868	2220

Source: Adapted from USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

economical design consists of a single pond, provided the system can be isolated enough to avoid complaints about odors when solids decompose on exposed slopes.

$$A = L \times W$$

$$L = W = A^{(1/2)} = 142.259 \text{ m}^{(1/2)} = 377 \text{ m (1237 ft)}$$

9.6.2.1.3 Summary

$$A = 142259 \text{ m}^2 \text{ (35 ac).}$$

$$W = 377 \text{ m (1237 ft).}$$

$$V = 170,800 \text{ m}^3 \text{ (45 MG).}$$

$$d = 1.2 \text{ m (3.9 ft).}$$

9.6.3 HYDROGRAPH CONTROLLED RELEASE

The hydrograph controlled release (HCR) pond is a variation of the controlled-discharge pond. This approach was first put into practice in the southern United States but can be used successfully in most areas of the world. The discharge periods are controlled by a gauging station in the receiving stream and are allowed to occur during high flow periods. During low flow periods, the effluent is stored in the HCR pond.

TABLE 9.15
Volume and Stage of Pond at Monthly Intervals for Design Conditions and A = 142,259 m²/m

Month	No. Days in Month	Inflow + Precipitation ^a (m ³)	Evaporation + Seepage ^b (m ³)	Storage Volume ^c (m ³)	Pond Stage Depth ^d (m)
Starting Date 1					
September	30	29,888	29,704	184	0
October	31	30,436	22,699	7921	0.06
November	30	29,561	15,620	21,862	0.15
December	31	31,403	11,318	41,947	0.29
January	31	31,076	10,891	62,131	0.44
February	28	28,209	14,977	75,363	0.53
March	31	30,763	21,419	84,708	0.60
April	30	28,977	25,436	88,249	0.62
May	31	29,739	35,075	82,912	0.58
June	30	28,693	39,093	72,513	0.51
July	31	30,293	43,042	59,764	0.42
August	31	31,588	35,929	55,423	0.39
Total		360,626	305,202		
Starting Date 2					
January	31	31,076	10,891	20,184	0.14
February	28	28,209	14,977	33,417	0.23
March	31	30,763	21,419	42,761	0.30
April	30	28,977	25,436	46,303	0.33
May	31	29,739	35,075	40,966	0.29
June	30	28,693	39,093	30,566	0.21
July	31	30,293	43,042	17,817	0.13
August	31	31,588	35,929	13,476	0.09
September	30	29,888	29,704	13,661	0.10
October	31	30,436	22,699	21,397	0.15
November	30	29,561	15,620	35,338	0.25
December	31	31,403	11,318	55,423	0.39
Starting Date 3					
December	31	31,403	11,318	20,085	0.14
January	31	31,076	10,891	40,269	0.28
February	28	28,209	14,977	53,502	0.38
March	31	30,763	21,419	62,846	0.44
April	30	28,977	25,436	66,387	0.47
May	31	29,739	35,075	61,051	0.43
June	30	28,693	39,093	50,651	0.36
July	31	30,293	43,042	37,902	0.27
August	31	31,588	35,929	33,561	0.24
September	30	29,888	29,704	33,746	0.24
October	31	30,436	22,699	41,482	0.29
November	30	29,561	15,620	55,423	0.39

Source: Adapted from USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

^a Inflow = $Q(\text{days/month})$; precipitation = (monthly precipitation)(A).
^b Seepage = $0.00076 \text{ m/day} (\text{days/month})(A)$; evaporation = monthly evaporation(A).
^c Storage volume = cumulative sum of (inflow + precipitation) – (evaporation + seepage).
^d Pond stage = storage V/A.

TABLE 9.16
Volume and Stage of Pond at Monthly Intervals for Average Conditions
and A = 142,259 m²

Month in Average Year	No. Days in Month	Inflow + Precipitation (m ³)	Evaporation + Seepage (m ³)	Storage Volume (m ³)	Pond Stage Depth (m)
September	30	29,888	36,674	6786	0
October	31	30,436	21,561	8875	0.06
November	30	29,561	17,612	20,824	0.15
December	31	31,403	14,192	38,035	0.27
January	31	31,076	12,385	56,726	0.40
February	28	28,209	18,690	66,245	0.47
March	31	30,763	23,410	73,598	0.52
April	30	28,977	28,708	73,868	0.52
May	31	29,739	40,197	63,409	0.45
June	30	28,693	47,771	44,332	0.31
July	31	30,293	50,582	24,044	0.17
August	31	31,588	45,887	9744	0.07
Total		360,626	357,668		

Source: Adapted from USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

The process design uses conventional facultative or aerated ponds for the basic treatment, followed by the HCR cell for storage or discharge. No treatment allowances are made during design for the residence time in the HCR cell; its sole function is storage. Depending on stream flow conditions, storage needs may range from 30 to 120 days. The design maximum water level in the HCR cell is typically about 2.4 m (8 ft), with the minimum water level at 0.6 m (2 ft). Other physical elements are similar to conventional pond systems. The major advantage of the HCR system is the possibility of utilizing lower discharge standards during high flow conditions as compared to a system designed for very stringent low flow requirements operated on a continuous basis.

DID YOU KNOW?

In certain situations, it is desirable to design pond systems in various combinations, such as an anaerobic or aerated pond followed by a facultative or a polishing pond (Li et al., 2006). These combinations use the same design as the individual ponds.

Zirschsky and Thomas (1987) performed a nationwide assessment of HCR systems which showed that they are effective, economical, and simple to operate. The authors also highlighted a basic principle of hydrograph controlled pond design basics: At critical low river flow, BOD_5 and TSS loadings are reduced by restricting effluent discharge rates rather than decreasing the concentration of pollutants. In addition, they observed that a pond system must be sized to retain wastewater during low flow (i.e., $Q_{10/7}$, such that flow equals once-in-10-year flow rate for a 7-day period). Another important design basic is to use existing ponds or build storage ponds. Moreover, the assimilative capacity of receiving streams must be established by studying historical or estimated data (Hill and Zitta, 1982). The bottom line is that HCR systems have been found to be an effective means of upgrading a pond effluent (USEPA, 2011).

9.7 PERFORMANCE COMPARISONS WITH OTHER REMOVAL METHODS

Designers and owners of small systems are strongly encouraged to use as simple a technology as feasible. Experience has shown that small communities or larger municipalities without properly trained operating personnel and access to spare parts inevitably encounter serious maintenance problems with the use of sophisticated technology and frequently fail to meet effluent standards. Methods discussed in this chapter that require good maintenance and operator skills are dissolved air flotation, centrifugation, coagulation–flocculation, and granular media filtration (rapid sand or mixed-media filters with chemical addition). At locations where operation and maintenance are available, these processes can be made to work well.

There are many methods of removing or controlling algae concentrations in pond effluents. Selection of the proper method for a particular site is dependent on many variables. Small communities with limited resources and untrained operating personnel should select as simple a system as is suitable to the site situation.

In rural areas with adequate land, ponds such as controlled-discharge ponds or hydrograph controlled release ponds are an appropriate choice. In arid areas, the total containment pond should be considered. Performance by these types of treatment is controlled by selecting the time of discharge and can be managed to produce an effluent (BOD_5 and TSS < 30 mg/L) that meets compliance standards.

Where land is limited and resources and personnel are not available, it is best to utilize relatively simple methods to control algae in effluents. Intermittent sand filters, application of effluent to farmlands, overland flow, rapid infiltration, constructed wetlands, and rock filters are reasonable choices. Intermittent sand filters with low application rates and a warm climate will provide nitrification. Application to farm land will reduce both nitrogen and phosphorus, while producing a satisfactory effluent.

9.7.1 WASTEWATER EFFLUENT APPLICATION VIA SLOW-RATE IRRIGATION

Land treatment using wastewater effluent for the irrigation of crops and forest products is not new. Wastewater treatment stabilization pond effluent is discharged continuously or intermittently to the environment. Utilization of wastewater influent for

irrigation is a beneficial reuse procedure that is gaining attention as a viable disposal methodology. There are three classifications of land treatment systems commonly used: slow-rate systems, high-rate systems (infiltration–percolation), and overland flow systems. Slow-rate systems are conventional irrigation systems where a crop is grown. In most instances, sale of this crop partially offsets treatment costs. Of the three systems, slow-rate systems are the most conducive to agricultural production (USEPA, 1979).

The potential advantages of this system are expansion of existing agriculture, improved production of existing farmland, reduction in the amount of fertilizer used by farmers, replacement of a water supply than can be delivered to other users, and excellent treatment of wastewater. The disadvantages are primarily in administering the program. If the authority chooses to operate its own system (e.g., Muskegon approach), then a total farming operation must be provided. This includes hiring an agronomist or agricultural engineer, farm equipment operators, and irrigation operators. There is also a major investment in land and equipment. If the authority chooses to contract with a local farmer or group of farmers, there are long-term contracts to work out. These disadvantages should rarely prevent project implementation.

9.7.1.1 Treatment Requirements

Requirements for wastewater treatment prior to application to the land by slow-rate systems are variable depending on the local regulatory agency requirements. Treatment requirements should be based primarily on the type of crops grown. Crops grown for animal consumption require less treatment than crops consumed by humans. If irrigation water does not contact fruit or vegetables, then treatment requirements are less stringent than systems where water contacts the fruit or vegetables. For example, if an orchard is spray irrigated, then the water may come into direct contact with the fruit. If the orchard is irrigated by a surface flooding system, then irrigation water will not come into contact with the fruit. Obviously, the latter method of irrigation requires less stringent treatment standards than the former.

9.7.1.2 Objectives and Degree of Treatment

Slow-rate systems are capable of providing a very high degree of treatment with very high levels of removal of BOD, suspended solids, and phosphorus under a wide range of soil and crop conditions. However, the removal of nitrogen can vary significantly depending on crop management. Assuming that runoff water is collected and recycled, the constituent that is of concern is nitrate nitrogen. This is correct for domestic wastewater or domestic combined with industrial wastewater, assuming industries have met USEPA pretreatment standards. Systems with unusual chemical or toxic elements must be evaluated on a case-by-case basis. The concern for nitrate nitrogen is less of a problem with slow-rate systems than high-rate systems, as crop harvesting provides a nitrogen removal mechanism. Nitrate concentrations are a concern with systems where underlying groundwater systems are used for domestic water supply. Water applied at agronomic rates will normally not be a hazard to groundwater. Water applied at rates in excess of crop needs may cause an undesirable increase in nitrate concentrations.

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10 Operation, Maintenance, and Troubleshooting

10.1 INTRODUCTION

The information presented in this chapter covers various topics related to the operation, maintenance, and troubleshooting of a pond, including control testing, safety, and optimizing operations. Much that has been written on these topics in the past 30 years remains valuable but may not be readily available. This chapter summarizes much of that information and brings it up to date. It introduces the basic tools used to monitor an operating pond treatment system and provides guidance when the system does not seem to be functioning as designed (USEPA, 2011).

10.2 CONTROL TESTING INFORMATION

For a facility to be consistently in compliance with discharge permit requirements, adequate process controls must be in place. The influent quantity and quality should be monitored on a regular schedule to provide the information needed to treat the wastewater stream adequately and operate the facility properly. It is also necessary to monitor the processes within the system in order to solve any effluent water quality problems. The influent, the internal pond processes, and the plant effluent should be evaluated on a regular basis. The bottom line is that, to remain in compliance and to meet the necessary permit sampling and analyzing requirements discussed below, a full-time staff of licensed operators is required to make hourly rounds to properly monitor and operate the wastewater stabilization pond and its associated auxiliaries (pumps, chemical feeders, valves, etc.).

A number of water quality parameters must be analyzed. Typical tests and measurements include flow, temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD_5), soluble BOD_5 ($SBOD_5$), carbonaceous BOD_5 ($CBOD_5$), total suspended solids (TSS), ammonia (NH_3), phosphorus, coliform (fecal or total), and chlorine (Cl^-) residual. The results of these tests are used to determine whether the treatment process is reducing the wastewater contaminants and to predict the impact of potential operational changes. Some of the tests can be performed with basic equipment (flow, temperature, pH, DO, and Cl^- residual), but some require more time, specialized equipment, and technical expertise (BOD_5 , $SBOD_5$, $CBOD_5$, TSS, NH_3 , and coliform). The operator of a small pond system may elect to collect samples for these tests and have a commercial lab complete some of the analyses (USEPA, 1977a).

All facility operators will need to review the facility discharge permit to determine the sample parameters to be tested, sample type, location, and frequency necessary to meet permit compliance. Operators of systems that have a controlled discharge will need to perform tests during the period prior to and during discharge as required by the regulatory agency. Systems operating on a hydrograph controlled-release discharge basis must monitor the treatment plant process and the quantity and quality of both the effluent and the receiving stream.

10.2.1 SAMPLE COLLECTION

Samples collected for analysis must be representative of the water being tested which requires that they be taken at a location where the wastewater is well mixed and not subject to short-circuiting. If the sample is to be stored before testing, it must be refrigerated. Sample containers must always be cleaned to method specifications before sampling to avoid confounding the results with background contamination. Temperature, pH, Cl^- residual, and DO should always be taken in the field to prevent false readings and should be taken at the same time each day. These parameters should be measured at other times of the day from time to time to gain an understanding of the changes that occur throughout the day.

10.2.2 TYPES OF SAMPLES

10.2.2.1 Grab Samples

Grab samples, taken at no set time or flow, are used to measure temperature, pH, DO, fecal and total coliform, and Cl^- residual. As raw sewage flow varies in content, as well as volume, over the course of the day, samples taken at sunrise and in mid-afternoon and analyzed separately will yield the most useful information. Grab samples of effluent from controlled-discharge ponds should be taken during discharge, perhaps one sample every two hours, but then should be combined into one composite sample. The operator should review state guidelines for specific information.

10.2.2.2 Composite Samples

10.2.2.2.1 Volumetric Composite

A volumetric sample is taken by collecting individual samples at regular intervals over a selected period of time, usually using a sampling device designed for this purpose. The samples must be refrigerated. They are then mixed together and considered to be a representative sample for whatever analysis is being performed.

10.2.2.2.2 Flow Proportional Composite

A flow proportional composite is taken by collecting individual samples at regular intervals over a selected period of time. A flow measurement is taken and recorded at the time the individual sample is collected. All samples must be refrigerated. At the end of the sampling period, each sample is stirred and an amount that is proportional to the flow at the time the sample was taken is poured into the composite container.

10.2.2.2.3 *Automatic Samplers*

There are numerous types of automatic samplers on the market. Some are self-contained with battery packs, while others must have an external power source. They take samples at chosen intervals, some as frequently as every 10 minutes, and composite the samples as they are collected. The samplers can be connected to existing flow measuring devices or may have built-in flumes that deliver flow-proportional composite samples. This equipment is most useful for sampling raw wastewater flow but can be used for effluent, as well.

10.2.3 HANDLING AND PRESERVATION OF SAMPLES

Sewage samples rapidly undergo biochemical changes if they are subjected to summer temperatures or freezing temperatures or if exposed to sunlight. Thus, collected samples should be transferred as soon as possible to a refrigerator. Keeping samples at a temperature of 4°C reduces post-collection biochemical changes for 24 hours. Samples taken for bacterial analyses should be collected separately and analyzed or sent to a laboratory for analysis with 30 hours of collection. Containers used for sample storage should be as clean as required for the specified method of analysis. Stoppered glass bottles or wide-mouthed jars are preferred and are easiest to use for mixing and cleaning. Bacterial samples should be collected in sterile containers.

10.2.4 SAMPLE POINT LOCATIONS

10.2.4.1 Pond Influent

Samples of the raw wastewater can be collected at the wet well of the influent pump station, a manhole at the inlet diversion control structure, or the influent headworks.

10.2.4.2 In Pond

Pond composite sample should consist of four equal portions taken from four corners of the pond. The samples should be collected 2.4 m out from the water's edge and 0.3 m below the water surface or at the transfer structures between the cells if these are present. Care should be taken to avoid stirring up material from the pond bottom, and samples should not be taken near mechanical aerators or during or immediately after high winds or strong storms, as these processes may stir solids into the water column.

10.2.4.3 Effluent

Effluent samples can be collected from the final cell outlet structure or at a well-mixed location in the outfall channel prior to mixing with any dilution waters such as the receiving stream waters.

10.2.5 TESTS AND MEASUREMENTS

Test results, along with visual indicators, are used by the operator to evaluate whether the pond is in discharge permit compliance. The following discussion describes these tests.

10.2.5.1 Temperature

The temperature of the influent wastewater can be used to detect inflow and infiltration (I&I) and some industrial wastes. A sudden increase in temperature may indicate the presence of warm industrial wastes. On the other hand, influent temperatures may cool rapidly in late fall and early winter. In one case, an investigation of the collection system revealed that owners of poorly insulated homes were bleeding their internal plumbing systems to prevent freezing of the pipes. This cold water diluted the influent sewage strength and cooled the temperature, which reduced the ability of the system to treat the waste.

Temperature can also be used to predict treatment efficiency and mode of operation (parallel or series) and estimate the necessary hydraulic retention time (HRT). As influent water temperature cools, a facultative pond system may need to be changed from series to parallel operation to reduce organic loading to each cell. A mechanically aerated pond system subject to cooler ambient temperature may have to have all cells in series operation to obtain the correct HRT for continuous permit compliance. Conversely, as influent water temperature increases, a facultative pond system may have to be changed from parallel to series operation. The operator of a mechanically aerated pond system may choose to remove an individual cell from operation to reduce the overall HRT and prevent a possible algal overgrowth condition.

10.2.5.2 Flow

Keeping a record of accurate flow measurements is essential for successful operation and control and for troubleshooting pond systems. Influent flow measurement can be used to detect I&I problems, determine the HRT of a cell, calculate the organic loading to a cell, provide data for determining mode of operation, and calculate appropriate chemical dosages. Effluent flow measurement is a requirement of the discharge permit and can be used to calculate the chemical dosage required for disinfection. Most states require both influent and effluent flow measurement to determine the extent of infiltration and/or exfiltration from the cells, depending on the distance of the system to groundwater.

10.2.5.3 pH Value

Large fluxes in influent pH may signal an industrial or septic waste problem. The range of pH for normal domestic influent waste is 6.8 to 7.5, depending on the alkalinity and hardness of the water. The pH is a good indicator of the health of the pond system. Pond cells that have a dark green color generally have a high number of green algae and a corresponding high pH. Algae take up carbon dioxide (CO_2) in the photosynthetic process. If CO_2 is not available, the algae will utilize a carbon source from the bicarbonate (HCO_3^-) alkalinity, which drives up the pH to 9.5 or above. At night, both the algae and aerobic bacteria utilize O_2 and produce CO_2 . The CO_2 in solution forms carbonic acid (H_2CO_3) and drives the pH down. These diurnal pH patterns are indicators of internal pond conditions. Pond cells that appear black or gray in color and have a decreasing pH value (<6.8) may be septic or moving toward a septic condition.

10.2.5.4 Dissolved Oxygen

Dissolved oxygen is an essential indicator of aerobic biological activity. The DO test is performed on a grab sample and must be performed immediately. The easiest method for analyzing for DO is with a portable meter. The test should be performed at sunrise and again at around 2 to 3 p.m. Large fluctuations in the primary cell may signal problems with the influent, such as shock loading or toxic waste issues. Some fluctuation in day-to-day DO in the pond system is expected. The operator should plot daily readings and identify trends in concentrations. A decreasing trend in DO in the early morning test may indicate an increasing organic load, a developing short-circuiting problem, or an algal overgrowth problem. Every effort should be made to avoid allowing the DO concentration to drop to zero. This will cause incomplete treatment of the wastewater and will result in discharge permit violations. The operator may have to take corrective action, such as increasing aerator running time or aeration capacity or switching to parallel operation. An increasing trend in the DO concentration, on the other hand, may allow the operator to decrease aerator running time or switch from parallel to series operation.

10.2.5.5 Dissolved Oxygen Profile

A DO profile is developed by taking a series of DO measurements at 0.3-m increments from top to bottom on an individual cell. An informal grid system is established to ensure uniform coverage of the cell (see Figure 10.1). This test is best performed by two people for safety reasons and data recording needs. A boat and a

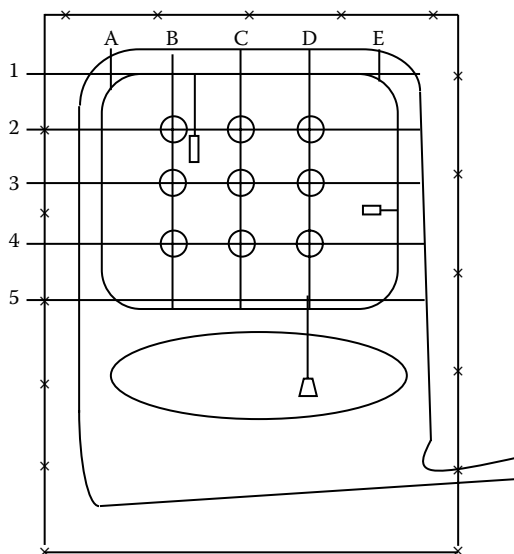


FIGURE 10.1 Sampling grid system. Sampling points are located where lines with letters and numerals intersect. (Adapted from USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.)

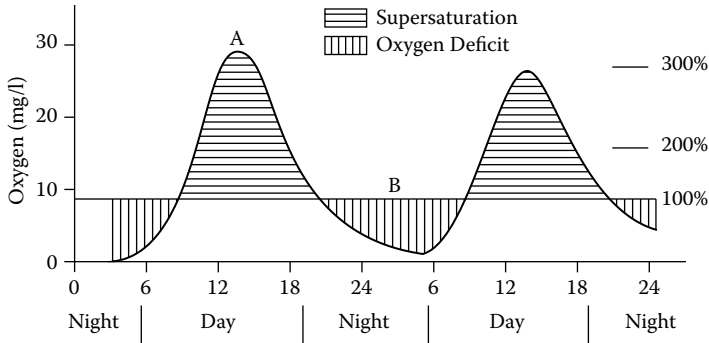


FIGURE 10.2 Diurnal O_2 curve. (Adapted from USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.)

portable temperature-compensating DO meter with a long probe are required. The probe should be marked off in 0.3-m increments from the tip of the probe to a length that will allow the operator to have the probe touch the bottom of the cell from the boat. The water depth at which the probe goes slack should be recorded.

This test allows the operator to determine if there is a DO deficit during evening hours when O_2 depletion is greatest due to biological activity. The test will also indicate if the pond is completely mixed or stratified, identify areas of low DO or dead spots, draw attention to short-circuiting, and help define bottom pond contours and areas of possible sludge buildup. The test should be performed just as it is getting light. As is seen in Figure 10.2, the lowest O_2 reading is noted just prior to sunrise. Once it is daylight, the algae photosynthesize, which may result in a supersaturated DO condition in early afternoon. As light intensity lessens and photosynthetic activity diminishes, O_2 is depleted. During the night, if the DO level in the pond drops to zero, aerobic decomposition of organic matter stops, causing incomplete treatment. This can lead to BOD_5 permit violations.

Note that the graph shows that the lowest DO levels occur early in the morning due to the aerobic bacteria and algae utilizing oxygen during the night. The highest dissolved oxygen level is late in the afternoon due to algal photosynthesis. It is likely that aerators must run more at night to compensate for the algae metabolizing oxygen. It is important to ensure proper aerator operation during the day for adequate mixing and to eliminate potential stratification.

10.2.5.6 Chlorine Residual

The Cl^- residual test determines the amount of Cl^- present after the detention time for disinfection (to destroy fecal coliform) has been met. The general rule is that there should be 0.5 mg/L remaining after a contact time of 1 hour. This grab sample must be tested immediately. The operator should review the National Pollutant Discharge Elimination System (NPDES) permit, as some states may not require disinfection. Some states may designate a prescribed coliform minimum, and some may require dechlorination after disinfection.

10.2.5.7 BOD₅

The BOD₅ test measures the amount of O₂ used by the microorganisms when metabolizing the organic material in a sample of wastewater. It is an indirect measurement of the relative organic strength of a sample. The test is performed over 5 days in a controlled environment. The sample is placed in an incubator at 20°C with no light or additional O₂. The test is used to determine the organic strength of the influent waste, calculate the organic loading to the pond system or an individual cell, make decisions about operational changes, and determine whether the effluent is in compliance with the discharge permit. The BOD₅ test can be misleading if there is a high concentration of algae in the effluent discharge. The BOD₅ test is an O₂ depletion test that is run in the dark. When algae are in the dark for long periods of time they cannot photosynthesize and will instead use O₂. The uptake by the algae also reduces the O₂ concentration at the end of the 5-day period. The result is a calculated BOD₅ value that is higher than it would be if it measured the organic loading from wastewater alone.

10.2.5.8 Soluble BOD₅

For this test, the BOD₅ sample is filtered using a 0.45-μm filter before the test is run. The filter should be observed for any obvious change and the color noted. The filtrate is then prepared in the same way and run at 20°C in the dark. It is recommended that a standard BOD₅ test and a soluble (filtered) BOD₅ test be run at the same time and the results compared. This is a valuable troubleshooting tool that will be discussed later.

10.2.5.9 Carbonaceous BOD₅

It has long been recognized that ponds will nitrify (convert NH₃ to nitrate [NO₃]) under certain conditions. This process uses approximately 1.8 kg O₂ per 453 g of NH₃ converted to NO₃ and approximately 4.1 kg of alkalinity per 453 g NH₃ converted to NO₃. The nitrification process will continue in the BOD₅ bottle, causing a higher BOD₅ test result. To compensate for this nitrogenous BOD in effluent BOD₅ testing, a CBOD₅ test can be substituted for the BOD₅ test. A CBOD₅ test is a BOD₅ test with inhibitor added to prevent O₂ depletion due to nitrification. To compensate for nitrification effects, regulatory agencies may allow operators to amend the discharge permit to substitute a CBOD₅ effluent limit for the BOD₅ parameter.

10.2.5.10 Suspended Solids

The suspended solids test measures the dry weight of solids retained on a glass fiber or Millipore™ filter and is expressed in mg/L. Equipment required for this test includes a drying oven, a desiccator, and a weighing balance. Tests must always be run on composited samples from both the influent and effluent. Suspended solids removal is as important as BOD₅ removal in preventing stream pollution. In normal domestic sewage, the concentrations of TSS and BOD₅ are similar. The origin of the suspended solids in the influent is not the same as in the effluent, however, as the former comes from the sewage, while the latter comes from algae growing in the final pond. As a result, the TSS may be higher than the BOD₅ in the effluent from pond systems.

10.2.5.11 TSS-to-BOD₅ Ratio

Effluent BOD₅ violations are often accompanied by high effluent TSS concentrations. The following TSS-to-BOD₅ ratios may be used as problem indicators (Richard and Bowman, 1997):

- <1, old sludge solubilization and release of soluble BOD₅ nitrification in the BOD₅ test bottle
- 1, poor treatment or short circuiting with untreated wastewater mixing with the effluent
- 1.5, normal for most pond systems
- 2.0–3.0, algal overgrowth; loss of old sludge particles

10.2.5.12 Microscopic Solids Analysis

The microscopic solids analysis is a test performed with samples from each pond cell taken at the transfer point and the final effluent before chlorination (Richard and Bowman, 1991). This requires the microscopic examination of fresh pond samples using a phase-contrast microscope capable of achieving a total magnification of 1000×. The types of solids present and their relative abundance are measured. Solids type categories include: (1) raw wastewater or sludge solids, (2) treatment solids (bacterial flocs), (3) filamentous bacteria, (4) sulfur bacteria, and (5) algae. These solids types are easily recognized with a little experience (Richard and Bowman, 1997). The significance of these solids types is listed in Table 10.1.

10.2.5.13 Soluble and Total BOD₅

The difference between these two values is the amount of particulate BOD₅ present. A typical domestic wastewater contains 40% soluble and 60% particulate BOD₅. The soluble BOD₅ is rapidly removed in wastewater treatment, and it is unusual to see a soluble BOD₅ in the effluent that is greater than 20% of the total. A particulate BOD₅ value greater than 70% of the total BOD₅ in the effluent indicates a solids loss problem. The microscopic examination is then used to identify the types of solids being lost (Richard and Bowman, 1997).

TABLE 10.1
Problems Associated with Types of Solids in Ponds

Solids Type Present	Indicated Problem
Raw wastewater solids	Short-circuiting, poor aeration, improper waste stabilization
Old sludge particles	Sludge buildup and need for sludge removal
Treatment solids (bacterial flocs)	Organic overloading or sludge accumulation
Filamentous bacteria	Low oxygen conditions or septicity
Sulfur bacteria	Anaerobic conditions and sulfides
Algae	Algal overgrowth

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

DID YOU KNOW?

Fecal coliforms are widespread in nature. All members of the total coliform group can occur in human feces, but some can also be present in animal manure, soil, and submerged wood, as well as in other places outside the human body. The usefulness of total coliforms as an indicator of fecal contamination depends on the extent to which the bacteria species found are fecal and human in origin. For recreational waters, total coliforms are no longer recommended as an indicator. For drinking water, total coliforms are still the standard test, because their presence indicates contamination of a water supply by an outside source. Fecal coliforms, a subset of total coliform bacteria, are more fecal specific in origin; however, even this group contains a genus, *Klebsiella*, with species that are not necessarily fecal in origin. *Klebsiella* are commonly associated with textile and pulp and paper mill wastes. If these sources discharge to a local stream, consideration should be given to monitoring more fecal and human-specific bacteria. For recreational waters, this group was the primary bacteria indicator until relatively recently, when the USEPA began recommending *Escherichia coli* and enterococci as better indicators of health risks from water contact. Fecal coliforms are still being used in many states as indicator bacteria.

10.2.5.14 Microbial Tests

The coliform and other microbial tests (total and fecal coliform, *Escherichia coli*, and enterococci) indicate the possible presence or absence of pathogens (human disease-causing organisms). The sources of this group of organisms are the excreta of humans, mammals, and birds. Tests are always run on grab samples collected in a sterile container. Recent regulations regarding which test method may be used for a particular discharge requirement may be found in USEPA (2007).

10.2.5.15 Nitrogen

Wastewater contains organic nitrogen (protein) and NH_3 . Organic nitrogen is converted to NH_3 by bacteria as protein is broken down. The NH_3 is further oxidized to NO_2^- and then to NO_3^- by nitrifying bacteria. This latter step is called *nitrification*. In some cases, it is necessary to remove NO_3^- in order to control algal growth. Oxygen is removed under anaerobic conditions (NO_3^- is a source of O_2 for the anaerobic bacteria) and NO_3^- is reduced to nitrogen gas (N_2). This is the denitrification step.

Ponds will nitrify and produce low effluent NH_3 concentrations under certain conditions, particularly in the warmer months of the year. As wintertime cools the wastewater temperatures, longer HRTs are required to rescue both CBOD_5 and nitrogenous BOD_5 . Ultimately, nitrification will cease at approximately 5 to 8°C. In colder climates, ponds cease to nitrify and will actually produce NH_3 in the wintertime and early spring. Installation of floating insulated covers may extend the period of time a pond will nitrify NH_3 . Low DO and low alkalinity can also limit nitrification. Typically, DO levels of 2.0 mg/L are required to optimize nitrification.

Total carbonate (CO_3^{2-}) alkalinity of less than 60 mg/L usually limits nitrification. Nitrification can be increased or prolonged by raising the DO level in the pond and increasing the alkalinity by adding an inorganic carbon source such as lime.

10.2.6 IMPORTANT VISUAL AND OLFACTORY OBSERVATIONS

Operators' visual and olfactory observations are important pond troubleshooting tools. Color and odor can be important indicators of pond health and the ability to meet discharge permit standards (Table 10.2).

10.2.7 OTHER DATA

10.2.7.1 Weather

Weather plays a major role in an operator's ability to meet discharge permit requirements for a pond system consistently. The operator should keep a daily journal or log of periods of sunshine, cloudiness, air and pond temperature, precipitation (rain or snow level should be recorded), and percentage of the individual cells that are ice covered. Prolonged periods of cloudiness may increase the effluent BOD_5 and require the operator to make a change from series to parallel operation in a facultative pond system. In an aerated pond system, the operator may be required to increase aerator running time to ensure discharge permit compliance.

10.3 OPERATION AND MAINTENANCE OF PONDS

The following sections are summaries from USEPA (1977b). Two other sources of information about O&M for ponds are Kerri (2002) and Spellman (2013). Before discussing the specifics of wastewater stabilization pond operation and maintenance, it is important to list the most common maintenance problems associated with pond systems:

- Weed control (cattails and other rooted aquatic plants)
- Algae control (blue-green and associated floating algae mats)
- Burrowing animals (muskrats and turtles)
- Duckweed control and removal
- Floating sludge mats
- Dike vegetation (mowing and removing woody plants)
- Dike erosion (riprap and proper vegetation)
- Fence maintenance to restrict access
- Mechanical equipment (pumps, blowers, etc.)

10.3.1 OPERATION AND MAINTENANCE GUIDELINES FOR ANAEROBIC PONDS

10.3.1.1 Anaerobic Ponds

A well-operating anaerobic pond is covered entirely with a dense scum blanket, which helps to keep the pond anaerobic and minimizes foul odors.

TABLE 10.2**Important Indicators of Pond Health and Ability to Meet Discharge Permit Standards**

Pond Appearance	Odor	Microscopic Observation	Problem	Solution
Clear	None	Little suspended material	None	None
Brown	Earthy	Small bacterial flocs	None; usually good operation	None
Gray-black floating sludge gas bubbles on pond surface	Septic sewage	Precipitated sulfides in flocs; often filamentous sulfur bacteria	Organic overloading; low dissolved oxygen; influent sludge short-circuiting	Increase aeration capacity; add baffles or additional cells; improve inlet–outlet design recirculation; remove sludge accumulation
Green	Grassy or earthy	Green algal bloom	Algal bloom, pH often >9!; long detention time; organic underloading	Recirculate; add a settling pond or land discharge
Floating mats of blue–green algae	Fishy	Blue–green bacterial bloom	See above	Remove cells from operation; decrease water depth to decrease HRT (<i>Caution:</i> may increase algal bloom)
Red streaks	None or septic	High amounts of <i>Daphnia</i>	<i>Daphnia</i> overgrowth, often after algal bloom	Increase aerator running time; recirculate
Entirely red or pink	Septic (rotten-egg odor)	Sulfur bacteria (<i>Chromatium</i> spp.)	Anaerobic; gross organic overloading and under-aeration.	Increase aerator running time or increase aeration capacity; recirculate

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

10.3.1.2 Important Operation Considerations

- Keep the pond pH at or near neutral (pH = 7).
- Control odors by maintaining 0 mg/L DO and a heavy scum blanket.
- Keep records of flow, HRT, pH, BOD₅, and TSS.
- Include information on volatile acids, scum, and sludge depth.

10.3.1.3 Onsite Attendance

Maintaining an anaerobic pond requires full-time operator attention. These activities should be performed on a daily basis, on a regular schedule, and as needed:

- Maintain mechanical equipment.
- Keep pipelines, diversion boxes, and screens clean.
- Collect samples.
- Run lab tests.
- Perform housekeeping.

10.3.2 OPERATION AND MAINTENANCE GOALS FOR FACULTATIVE PONDS

10.3.2.1 Pond Effluent Compliance Conditions

The pond effluent should

- Meet the NPDES or other regulatory permit levels for BOD₅ and TSS for continuous flow systems.
- Discharge when the effluent has the best quality and will least affect the receiving stream.
- Have a deep green sparkling color in the primary pond.
- Have high DO levels in the secondary or final cells.

10.3.2.2 Wave Action

The surface water should have wave action when wind is blowing. The absence of good wave action may indicate anaerobic conditions or an oily surface.

10.3.2.3 Maintenance Guidelines

- To maintain wave action, a pond should be free of weeds in the water or tall weeds on the banks.
- Dikes should be well seeded with grasses above the water line. Grass should be mowed regularly to prevent soil erosion and insect problems.
- Rip, broken concrete rubble, or a poured concrete erosion pad should be placed at the water's edge to prevent erosion of dikes.
- Inlet and outlet structures should be cleaned regularly to remove any floating debris, caked scum, or other trash that might produce odors or be unsightly.
- Mechanical equipment should be maintained according to a regular schedule. Maintenance records should be kept and be readily accessible.
- All pond operations should be listed on a posted schedule. The plant records should include weather data and basic test results such as flow, pH, DO, BOD₅, TSS, and chlorine residuals.

10.3.3 OPERATION AND MAINTENANCE GOALS FOR AERATED PONDS

In the past, many of the facultative pond systems were converted to aerated pond systems by the addition of mechanical aeration. This allowed the hydraulic and organic loading rates to increase but caused many operational problems. Cell depths

remained shallow (1.2 to 1.8 m), and HRTs were typically lower than those used in facultative ponds but greater than those used in aerated pond systems. Some problems were caused by the surface aerators mixing too deeply and scouring the bottom of the cells, compromising the integrity of the liners. The shallow depths and longer HRTs promoted algal overgrowth, making it difficult to meet discharge permit requirements in the summer months. Aerated ponds require the same daily inspections and maintenance as any other treatment ponds. In addition, special attention must be paid to the aeration equipment. The following are minimal guidelines:

- Maintain a minimum of 1 mg/L DO throughout the pond at the heaviest loading periods.
- Run the system so that surface mechanical aerators produce good turbulence and a light amount of froth.
- Monitor DO at aerated cell daily.
- Keep large objects out of the pond to prevent damage to the aerator.

For diffused-air systems that use a blower and pipelines to diffuse air over entire bottom of pond,

- Check the blower daily.
- Visually inspect the aeration pattern for dead spots or dead lines.
- Check for ruptures and repair them if necessary to maintain even distribution of air.
- Measure DO at several locations in the pond weekly and adjust air to maintain even distribution.

Periodic maintenance, such as lubrication, adjustment, and replacement of parts, must be performed on a regular basis. A checklist of maintenance tasks and frequency, taken from the manufacturer's recommendations, should be available and activities relating to maintenance recorded in a log book.

10.3.4 POND SYSTEM CHECKLIST

A checklist is a handy tool for the operator to schedule activities. Most of the items are visual observations or maintenance needs that take little time if performed according to a regular schedule. Over time, the operator will develop ways to combine some of the duties. In many installations that are overseen regularly by a conscientious operator, the scheduled tasks can be accomplished in one or two hours a day, allowing the balance of the time to be used to complete laboratory work and other duties.

Table 10.3 is a sample O&M checklist for pond operation. Although it is not a complete list of everything the operator should be observing, it will serve as a guide for setting up a regular schedule and as a daily reminder. The schedule will help the operator organize work in a step-by-step fashion, which will also help operators coming on in relief during an emergency or new personnel who are not familiar with the system. The design engineer should develop a checklist for the system that is included in the O&M manual.

TABLE 10.3
Example Operation and Maintenance Checklist

	Frequency						
	Daily	Weekly	Monthly	3 Months	6 Months	Yearly	As Needed
Plant Survey							
<i>Drive around perimeters of ponds taking note of the following conditions.</i>							
Any buildup of scum on pond surface and discharge outlet boxes		✓					
Signs of burrowing animals	✓						
Anaerobic conditions, noted by odor and black color, floating sludge, large number of gas bubbles	✓						
Water-grown weeds	✓						
Evidence of dike erosion	✓						
Dike leakage	✓						
Fence damage	✓						
Ice buildup in winter						✓	✓
Evidence of short-circuiting	✓						
<i>A review of the information obtained from the observations should be included in the next year's planning activities.</i>							
Plan, schedule, and correct problems found. See the troubleshooting section of this chapter for more information.						✓	
Pretreatment							
Clean inlet and screens and properly dispose of trash.	✓						
Check inlet flow meter and float well	✓						
<i>If discharge is once or twice per year, the discharge permit may require observations of the following.</i>							
Odor		✓					
Aquatic plant coverage of pond		✓					
Pond depth		✓					
Dike condition		✓					

TABLE 10.3 (cont.)**Example Operation and Maintenance Checklist**

	Frequency						
	Daily	Weekly	Monthly	3 Months	6 Months	Yearly	As Needed
Ice cover		✓					
Flow (influent)	✓						
Rainfall (or snowfall)	✓						

Note: Each state has requirements for data collected prior to and during discharge that are defined in the pond system discharge permit.

If discharge is continuous, the discharge permit may require the following information.

Weather	✓						
Flow	✓						
Condition of all cells	✓						
Depth of all cells	✓						
Pond effluent							
DO and pH grab samples	✓						
Cl ⁻ residual	✓						
BOD ₅ and TSS run on composite sample							✓
Microbial tests							✓
Kg (lb) of Cl ⁻ used and remaining	✓						

Other tests and frequency information will be defined in the individual permit.

Mechanical Equipment

Check mechanical equipment and perform scheduled preventive maintenance on the following pieces of equipment according to the manufacturer's recommendations.

Pump stations:							
Remove debris	✓						
Check pump operation	✓						
Run emergency generator		✓					
Log running times	✓						
Clean floats, bubblers, other control devices		✓					
Lubricate							✓
Comminuting devices:							
Check cutters		✓					
Lubricate							✓

TABLE 10.3 (cont.)
Example Operation and Maintenance Checklist

	Frequency						
	Daily	Weekly	Monthly	3 Months	6 Months	Yearly	As Needed
Aerators:							
Log running time	✓						
Check amperage		✓					
Chlorinators:							
Check feed rate	✓						
Change cylinders							✓
Flow measuring devices:							
Check and clean floats, etc.	✓						
Verify accuracy		✓					
Valves and gates:							
Check to see if set correctly	✓						
Open and close to make sure they are operational		✓					

Source: USEPA, *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*, U.S. Environmental Protection Agency, Washington, DC, 2011.

10.3.5 FLEXIBLE DESIGN TO IMPROVE OPERATION

10.3.5.1 Flow Regulation

Flow regulation is one of the most helpful operational tools. Without the flexibility to move water around where it is needed, operators would be severely limited in their ability to troubleshoot and solve pond system problems.

10.3.5.1.1 Single-Cell Ponds

The only flexibility an operator has with a single-cell pond is depth control. The water level may have to be varied seasonally or to control weeds and mosquitoes.

10.3.5.1.2 Multiple-Cell Ponds

Multiple-cell pond systems may be operated to optimize a number of different parameters. They may be operated so as to

- Hold wastewater in the primary cell, especially during seasonal discharge operation.
- Move water from cell to cell to correct an O₂ deficiency problem.

- Control liquid depth to eliminate weeds or mosquitoes.
- Isolate a cell that has become anaerobic or to hold a toxic waste.
- Take advantage of both series and parallel operation to regulate loading.
- Rest a cell temporarily for recovery.
- Recirculate water from the last cell to the first cell, at a minimum. This allows the operator to increase the DO and to seed the first cell with algae. Remove an individual cell from operation that varies the HRT of the system, particularly in summer.

10.3.5.2 Baffles and Screens

Screens, often custom-made, are used around pond surface outlets to keep wind-blown weed and surface trash from entering a pipe. Baffles may consist of pilings (5 by 24 cm) driven into the pond bottom. They are commonly used for a large variety of purposes, such as the following:

- Direct the flow of water, especially around inlets.
- Reduce or eliminate short-circuiting.
- Allow selection of depth for pond draw-off and to keep surface scum and trash from entering.
- Provide a quiet zone ahead of a flow measuring device.
- Reduce the force of a pump discharge.

10.3.5.3 Inlet and Outlet Design

Submerged outlets should be used to prevent the discharge and/or transfer of floating material between ponds. Variable-depth draw-off is especially useful in parts of the country where algal overgrowth is a problem. The effluent should be able to be drawn from any depth in the pond cell, giving the operator the choice of transferring or discharging the best quality water. Variable-depth discharge works best with surface mechanical aeration. Low discharge approach velocities are required to minimize the area of influence adjacent to the discharge structure.

There are numerous discharge structure designs that allow the operator to draw effluent in the area under the algal layer while staying 0.6 to 0.9 m above the benthic sludge layer. At a minimum, the pond should be designed with three draw-off points: the first below the algae layer, the second at approximately mid-depth, and the third above the bottom of the pond. The use of properly designed inlet and outlet manifolds may aid in the distribution and collection of wastewater flows and minimize short-circuiting. Transverse perforated collection pipes may reduce approach velocities, increase the discharge collection area of influence, and help minimize short-circuiting. Having multiple inlets and outlets in the system design gives the operator greater flexibility to match the loading and discharge of a pond system more closely to environmental conditions (USEPA, 2011).

10.3.5.4 Dike Erosion

Wave erosion works on the banks of all unlined earth facilities. Wind generates waves that beat upon the side slopes, patiently nibbling away at the soils and causing continued sluffing problems. In time this action will cause sections of the embankment to

fall into the water as the material sluffs to the toe position. If this action continues long enough, the entire bank can be eroded away to the point where reservoir failure occurs.

Kays (1986, p. 205)

Dike erosion from wave action can be prevented by using riprap in the form of rocks 8 to 48 cm laid along the water's edge. One unusual method employed was to sink 5 × 15-cm uprights into the pond floor extending above the water surface to dissipate the waves. In another case, the pond operator filled bags with a dry mix of sand, gravel, and cement. These were laid side by side and stacked to form a system of riprap protection. Riprap should extend 0.3 m above and below extreme operating levels. Other forms of riprap for bank stabilization include cribbing (snow fence) laid on the bank and reed canary grass. Canary grass is effective in ponds that are deep and have steep slopes and a stable water level. If sod is used, it should be at least 7.5 cm (3 in.) square and placed not more than 1 m apart.

10.3.6 POND CLEANING

When it becomes necessary to clean a pond, the operator should first contact the regulatory agency to find out about any special requirements. In most cases, the operator or consulting engineer is required to develop a plan outlining the method of sludge removal, the steps to be taken to ensure pond liner integrity, and how the sludge to be removed will be tested for volatile solids and metals, in addition to describing the plan for ultimate disposal of the sludge. A separate permit may be required when land application of the sludge is selected for ultimate disposal. The regulatory agency may require site geological information (e.g., type of soil, slope of ground, depth to groundwater), type of crop grown and the agronomic uptake rate of metals and nutrients of that crop, sludge testing, method of application, method of solids incorporation into the soil, irrigation practices, runoff control and disposal, and, if applicable, vector control and monitoring requirements. The most common method of sludge removal is to employ some type of sludge pumping equipment. Care should be taken to maintain the integrity of the pond liner. Damage to a pond liner may require repair or replacement or, at a minimum, increased monitoring and testing to ensure that the pond is not adversely affecting surface water, groundwater, or public health.

10.3.7 PROCEDURES FOR STARTUP

10.3.7.1 Primary Cell

Spring or early summer is the best time for startup to avoid low temperatures and possible freezing. Fill primary cells with water from a river or municipal system, if available, to the 0.6-m level. Add the wastewater, keeping the pH above 9.5 and checking the DO daily. Algal blooms should appear in 7 to 14 days. A good biological community will be established in about 60 days or less. The color will be a definite green, not blue or yellow-green. This procedure tends to avoid odorous anaerobic conditions and weed growth during the startup phase. If it is necessary to start in late fall or winter, the water level should be brought to 0.75 to 1 m and not discharged until late spring.

10.3.7.2 Filling Successive Ponds

- Begin filling when the water level in the first pond reaches a depth of 1 m.
- Add fresh water to a depth of 0.6 m.
- Begin adding water from previous pond, observing the following:
 - Use top draw-off to achieve good transfer. Do not draw off from a level below the bottom 45 cm.
 - Do not allow the water depth in the previous ponds to fall below 1 m.
 - Equalize water depths in all ponds: Hold the discharge until all ponds are filled. Use an effluent box with gates or valves to allow pumping of the effluent to any pond in the system if it is designed with this capacity. Recycle the effluent continuously to the ponds with low water levels. Repeat the operation using 15-cm increments until ponds are at their operating depth.
- Begin continuous or intermittent discharge, according to the system design.

10.3.8 DISCHARGE CONTROL PROGRAM FOR SEASONAL DISCHARGES

10.3.8.1 Preparation

- Make a note of conditions in the stream to receive discharges.
- Estimate the duration of the discharge and expected volume.
- Obtain state regulatory agency approval.
- Isolate the cell to be discharged, and allow it to rest for at least one month, if possible.
- Arrange for daily sample analysis of BOD₅, TSS, pH, coliform, and nutrients (if required).
- Plan other work so as to be able to devote full attention to the control of discharge throughout the period.
- Sample contents of cell and analyze for DO; note and record turbidity, color, and any unusual conditions.

10.3.8.2 Discharge Procedures

Ponds in a number of northern states are permitted to discharge effluent seasonally. Three or four weeks after ice break-up, the ponds generally return to normal operating conditions. Wastewater in the cells is tested and results are reported to the state. If the wastewater is of a quality suitable for discharging, the operator follows state guidelines for discharging. The NPDES permit contains information about the discharge quality. The quality of the receiving stream is usually determined by the state water quality control agency as part of the discharge approval program. When discharge approval is obtained, proceed as follows:

- Begin the discharge program with the last cell in series.
- Draw off the discharge from the best level at a time when the discharge is acceptable.
- Stop the discharge when ponds are upset.
- Follow testing procedures outlined by the state regulatory agency.

10.4 POND SAFETY

Several statistical reports have indicated that the wastewater treatment industry and the operation of treatment ponds can be extremely unsafe (Spellman, 2000). This less than stellar historical safety performance record has continued to deteriorate, even in the age of the Occupational Safety and Health Act (OSH Act). As a case in point, consider the records from 1986 to 1987, when the accident frequency rate for wastewater treatment plant and stabilization pond/lagoon operations was 38, which was nearly four times the rate (10) for the average U.S. industry. For the same time period, the accident frequency rate for the worst industry reporting to the National Safety Council (NSC) was 40. Why is the on-the-job injury rate for the wastewater treatment industry so high? There are several reasons why. First, all of the major classifications of hazards exist at a wastewater treatment plant/pond:

- Oxygen deficiency
- Physical injuries
- Toxic gases and vapors
- Infections
- Fire
- Explosion
- Electrocution

Along with having all of the major classifications of hazards present, there are other factors contributing to the high incidence of injury. Some of these can be attributed to the following:

- Complex treatment systems
- Shift work
- New employees
- Liberal workers' compensation laws
- Absence of safety laws
- Absence of safe work practices and safety programs

Experience has shown that a lack of well-managed safety programs and safe work practices is a major reason why the wastewater treatment industry is ranked near the top of the NSC's worst industries with regard to worker safety. For this reason, the absence of safe work practices and safety programs is the focus of this discussion.

If the wastewater industry has such a high rate of on-the-job injuries, how can well-managed safety programs and safe work practices make a difference? To begin with, workers involved with wastewater work have a high incidence of injury because of the *diversity* of duties they must perform. The average wastewater worker must be a Jack or Jill of all trades. Routine functions performed by most wastewater operators include taking samples; operating, monitoring, and determining settings for chemical feed systems and high-pressure pumps; and performing laboratory tests and recording the results in the process daily operating log. It

is the non-routine functions, however, that cause the problems. For example, the typical wastewater operator not only must perform the routine functions but must also make emergency repairs to systems (e.g., welding a broken machine part to keep the equipment online), perform material handling operations, make chemical additions to process flow, respond to hazardous materials emergencies, perform site landscaping duties, and perform several other functions that are not usually part of the operator's job classification but are required to maintain satisfactory treatment process operation and site appearance. Remember, the treatment process operator's job is to *keep the system running*, and keeping the system running at 3:00 a.m. may require operators to perform mechanical tasks that they are not trained to do.

Because the wastewater treatment pond operator is expected to be a diverse, multitented, extremely capable individual who can do whatever is required to maintain smooth plant operation, several safety considerations come into play during a wastewater operator's normal work shift. Thus, there is a need for a wide variety of safety programs and safe work practices to cover a wide variety of diverse job functions. Remember, it logically follows that diverse job functions expose the stabilization pond worker to a myriad of hazards.

10.4.1 PUBLIC HEALTH

Operators and others conducting activities around treatment ponds must proceed with caution and make safety and public health a priority. Treatment ponds must be utilized for their designed purpose only, not for public recreation. The relative amount of water surface of treatment ponds is insignificant compared to the many natural bodies of open water in most localities. In some areas, however, treatment ponds represent the only sizeable body of water and have been sources of attraction for recreation purposes. Incidents of boating, ice skating, waterfowl hunting, and even swimming in ponds have been reported. Recreational use should be discouraged and safety practices encouraged for several important reasons. Even though the efficiency of bacterial removal as measured by the most probable number (MPN) method is very high, the possibility of contamination or infection from pathogenic organisms does exist when a person comes in contact with wastewater in a treatment pond. People can drown in treatment ponds. Clay and synthetic liners used in sealing ponds become very sticky when water is added. Should a person fall into a pond, the presence of liners would make it extremely difficult to get out. To discourage the use of ponds for recreation, the entire area should be fenced and warning signs displayed.

Another factor to be considered is the presence of mosquitoes. In a well-maintained pond system, mosquitoes usually are not a nuisance. According to studies by the U.S. Public Health Service, the density of the mosquito population is directly proportional to the extent of weed growth in a pond. Where weed growth in the ponds and along the water line of the dikes is negligible and where wind action on the pond is not unduly restricted, the likelihood of mosquitoes breeding is low.

10.4.2 PERSONAL HYGIENE

In the interest of the health of those who work around wastewater treatment ponds and their families, following is a list of recommendations regarding personal hygiene:

- Never eat or put anything into your mouth without first washing your hands.
- Refrain from smoking while working in manholes.
- Wear gloves when working on pumps or other parts of the operation where hands may become contaminated.
- Don't wear work coveralls or rubber boots in the car or at home.
- Always clean any equipment, such as safety belts, harnesses, face masks, or gloves, after use.
- Keep fingernails cut short and clean.

10.4.3 SAFETY

10.4.3.1 Sewer Maintenance Safety Practices

- Remove and replace heavy manhole covers carefully and only with the proper tools.
- Descend into any manhole slowly and cautiously.
- Use the buddy system; do not enter without a spotter present.
- Be aware of the potential for noxious gas generation, explosive mixtures, and oxygen deficiency in wastewater pond process operations; moreover, because of the potential for exposure to these hazards, pond operators must be in compliance with OSHA's Hazard Communication Standard (29 CFR 1910.1200), as explained below.

10.4.3.1.1 Noxious Gases, Explosive Mixtures, and Oxygen Deficiency

The principal air hazards associated with wastewater treatment are accumulations of sewer gas and its mixture with other gases or air, which may cause death or injury through explosion or asphyxiation as a result of an oxygen deficiency. The term "sewer gas" is generally applied to the mixture of gases in sewers and manholes containing high percentages of CO₂; varying amounts of methane (CH₄), hydrogen (H₂), and hydrogen sulfide (H₂S); and low percentages of O₂. Such mixtures sometimes accumulate in sewers and manholes where organic matter has been deposited and undergone decomposition. The actual hazards from sewer gas are due to the explosive amounts of CH₄ and H₂S present, as well as an oxygen deficiency. Hydrogen sulfide is toxic at very low concentrations, and a person's sensitivity to the odor is quickly deadened. Chlorine gas, which is irritating to the eyes, respiratory tract, and other mucous membranes, may settle in low-lying, still areas. The gas forms an acid in the presence of moisture. The gas may leak from cylinders and feed lines and diffuse and settle into these places.

10.4.3.1.2 OSHA's Hazard Communication Standard (29 CFR 1910.1200)

If workers come into contact with hazardous chemicals in the workplace, OSHA mandates that they have a "right to know" what chemicals they are working with or around. This employee "right to know" requirement is formally known as OSHA's

Hazard Communication Standard. This standard requires that the manufacturers, importers, and distributors of the hazardous chemicals must transmit important information to employees in the form of container labels and Material Safety Data Sheets (MSDSs). The information contained on the label or MSDS must clearly state the possible physical or health hazards of each chemical (Spellman, 2000). For pond operators, generic MSDSs should be developed by management (utilizing the expertise of safety professionals) to make available to operators (24/7) pertinent information and warnings about treatment pond hazardous gases or chemicals they may be exposed to during the performance of their normal operating duties.

Under the Hazard Communication Standard, the employer is required to ensure that each chemical is properly labeled. In addition, the employer is required to label hazards that might be produced by a process; for example, in the wastewater industry, it is not unusual for deadly methane gas to be generated in the wastestream. Another process hazard that is common in the wastewater industry is the generation of hydrogen sulfide gas. Hydrogen sulfide is generated during degradation of organic substances in the wastestream. The Hazard Communication Standard requires the employer to label these methane and hydrogen sulfide hazards to warn workers of the hazards and to ensure that safety precautions are followed.

Labels must be designed to be clearly understood by all workers. In addition, employers are required to provide both training and written materials to make workers aware of what they are working with and what hazards they might be exposed to. Moreover, employers are required to make Material Safety Data Sheets available to all employees. The facility Hazard Communication Program must be in writing and, along with MSDSs, made available to all workers 24 hours each day/shift.

The MSDS provides seven or more sections of information on a particular hazardous material (hazmat). Section 1 identifies the hazmat and the chemical components that it contains. Section 2 provides important physical and chemical characteristics. The hazardous materials emergency responder must pay particularly close attention to this section. As a case in point, suppose your plant site has a chlorine spill and emergency response is required to mitigate the spill. The first item the emergency responder should seek out is the MSDS for chlorine. From the MSDS for chlorine, the emergency responder can quickly determine that chlorine has a vapor density of 2.5. This means that chlorine gas is 2.5 times heavier than air and will seek out any low spots near the spill. Additionally, the emergency responder will find on the MSDS for chlorine that as a gas chlorine is a respiratory hazard that can kill. This could be life-saving information for the responder who might have to rescue someone from an underground vault or storage space.

Section 3 of the MSDS provides important information on the hazmat's fire and explosion potential. Whenever the local fire department is called to the scene of a hazmat emergency, the responders are very interested in the fire and explosive potential of the material spilled. This is especially the case whenever a hazmat incident includes fire. Section 4 provides information concerning the reactivity of the hazmat. Reactivity refers to the stability of the material. A hazmat such as nitroglycerin is extremely unstable and must be handled with great care. On the other hand, a substance such as acetone is fairly stable or nonreactive. Section 5 covers information related to the health hazards associated with the hazmat. Important information

relative to the primary routes of entry into the body by inhalation, ingestion, and/or skin absorption is covered. Additionally, the MSDS points out whether or not the hazmat may cause acute or chronic health problems. Additionally, emergency first-aid procedures are listed in this section. This is critical information, especially if a worker is exposed to the hazmat. If the worker's eyes, skin, respiratory system, or internal digestive tract is contaminated with the hazmat, the emergency responder needs to know immediately what emergency medical response actions to take.

Personal protective equipment (PPE) is listed in Section 6 of the MSDS. It is important for workers to know how to protect themselves from the lethal effects of the hazmat. Employees who are working with or around a particular hazardous material need to pay close attention to this section. This section details the respiratory protection, eye protection, hand protection, and protective clothing and equipment that might be required to work safely with the hazmat. In addition, Section 6 addresses the kind of ventilation that might be required to make the hazmat environment safe to work in. Another part of Section 6 that has direct implications to the wastewater industry is the hygienic work practices. Remember, wastewater workers are constantly exposed to the biological hazards associated with handling untreated wastewater. This kind of hazardous exposure potential can be greatly magnified whenever hazmats are thrown into the equation. The last section, Section 7, points out the correct steps to be taken during a hazmat leak or spill. Hazmat workers need to remember that whenever they are working with a hazmat and the hazmat is spilled or released to the environment they are no longer working with a hazmat but instead are now working with a hazardous waste. Section 7 addresses the proper hazardous waste disposal methods; this is important. Moreover, if there are any special precautions to be taken or hazards to be aware of, Section 7 also addresses these items.

Before leaving this discussion of OSHA's Hazard Communication Standard and the requirements for compliance, it is important to point out that no matter the size wastewater treatment facility or wastewater stabilization pond where you work, you must comply with this standard. This information may surprise a large number of chief operators who work at local publicly owned treatment works (POTWs). At a small wastewater facility, the thinking usually revolves around the facility's size; that is, most small facility operators usually think that because they are only a one- or two-person operation they do not use or produce hazardous materials in their processes and therefore are exempt from OSHA compliance. Nothing could be further from the truth. In order to check on whether or not a particular facility must comply with the Hazard Communication Standard, it is necessary to conduct a survey of your facility. During this plant survey, a determination should be made as to whether or not hazardous chemicals are used or produced. Remember, a process that does not use hazardous materials but does produce hazardous byproducts (e.g., methane, hydrogen sulfide) must be listed, as required in OSHA's Hazard Communication Standard, in the facility's written hazard communication program. At the very minimum, warning signs must be posted alerting workers and visitors of the potential hazard. Remember, the essence of OSHA's Hazard Communication Standard is that the *employee has a right to know*. This right to know also includes anyone who might be exposed to the hazard.

10.4.3.2 Pumping Station and Treatment Pond Safety Precautions

- Maintain a high level of housekeeping. Keep floors, walls, and equipment free from dirt, grease, and debris. Keep tools properly stored when not in use.
- Keep walkways clean and free of slippery substances. If ice forms on walks, apply salt or sand or cover with earth or ashes that can be removed later.
- Be especially cautious when working with an electrical distribution system and related facilities. Never work on electrical equipment and wires with wet hands or in wet clothes or shoes. Always wear appropriate safety gloves for electrical work. Never use a switchbox as anything other than a switchbox.
- Keep all personnel safety conscious by providing training at regular intervals. Have specific safety instructions posted in appropriate places. Such instructions should include information about, for example, contacting the nearest medical center and fire station, rescue techniques, resuscitation, and first-aid techniques.
- Make certain that a sufficient number of trained and experienced personnel with proper equipment are assigned and present whenever it is necessary to perform any hazardous work.
- Provide boating safety training. Life preservers must be used whenever personnel are in a boat on treatment ponds. At least two people should work together around the ponds because of the danger of drowning and other accidents. Safety training for a pond operator should include life-saving skills, including the ability to swim at least 30 minutes in normal work clothing.
- Place a sufficient number of fire extinguishers (Underwriters Laboratories approved) in readily accessible locations.

10.4.3.3 Body Infection and Disease Safety Precautions

Treat all cuts, skin abrasions, and similar injuries promptly. When working with wastewater, the smallest cut or scratch is potentially dangerous and should be cleaned and treated immediately with a 2% solution of tincture of iodine. In addition, personnel should

- Receive medical attention for all injuries.
- Be given first aid training.
- Be inoculated for waterborne disease, particularly typhoid and paratyphoid fever.
- Keep a record of all immunizations in an employee health record.
- Review records annually for necessary boosters and new immunizations.

In the laboratory, always use appropriate laboratory equipment and supplies, and avoid any contamination by mouth. Don't take laboratory glassware for personal use. Paper cups should be provided in laboratories for drinking purposes. Never prepare or eat food in a laboratory.

10.4.3.4 Safety Equipment

The importance of the employer providing and requiring personal protective equipment (PPE) and training for wastewater stabilization pond process operators cannot be overemphasized. It is important to note that PPE is to be used as a last resort in protecting workers. Work sites should be thoroughly evaluated for hazards, and these hazards should be removed prior to workers being required to perform work in them. In a perfect world, a hazard-free work environment is the goal. In the real world, however, not all hazards can be eliminated or engineered out of the workplace. Wastewater treatment and collection is one of those industries where hazards cannot be completely eliminated. For example, confined space entry and chemical handling activities are hazards that are inherent to the industry and cannot be easily removed or done away with. However, performing work in confined spaces (e.g., pump station wet wells, man-holes) and handling chemicals can be made safer if workers have the proper safety equipment available for use. To prevent injury and make any work place safer, regulators have mandated that employers must provide certain types and quantities of proper safety equipment to all workers. However, safety equipment is only as good as the material condition of the equipment and the proficiency of the workers who use the equipment. The importance of proper maintenance of safety equipment and providing safety training to workers cannot be overemphasized. In the following pages, some of the specific safety equipment that should be used while performing particular work activities within the wastewater treatment and collection industry is pointed out.

10.4.3.5 Safety Equipment and Confined Space Entry

10.4.3.5.1 Background

The permissible exposure limits (PELs) to protect workers from exposure or overexposure to hundreds of airborne contaminants are specified in OSHA's Air Contaminants Standard, 29 CFR 1910.1000, Subpart Z—Toxic Substances. The "Z Tables" list all of the exposure limits for each substance regulated by OSHA and tell you where to look for exposure information within the Code of Federal Regulations.

10.4.3.5.2 Air Monitoring

The Confined Space Entry Standard (29 CFR 1910.146) sets the guidelines for monitoring confined spaces. Prior to entry into a confined space, wastewater treatment facilities and collection systems are required to use air monitors for oxygen and for combustible and toxic gases that are commonly found in confined spaces. When air monitoring equipment is used to test the atmosphere of a confined space, it is important to follow the guidelines for testing and recording of test results that are provided on the Confined Space Entry Permit Form. The Confined Space Entry Permit Form is basically a checklist that lists the steps to be followed in order to ensure proper and safe confined space entry. Along with monitoring the atmosphere of confined spaces for air contaminants or lack of oxygen, the Confined Space Entry Permit Form and the Plant's Confined Space Entry Procedure should point out what type of additional safety equipment is required to protect workers when entry into the confined space is to be made. See Case Study 10.1 for an example of an actual incident regarding a fatal confined space entry.

CASE STUDY 10.1

A construction crew obtained a contract from an industrial complex to clean and preserve the interior surface of a large chemical storage tank. The construction crew was not familiar with OSHA's Confined Space Entry Permit Standard. When the construction workers arrived at the work site and peered inside the tank, they quickly realized from the horrendous stench emanating from the interior of the tank that it might not be a safe environment in which to work. The crew foreman had an idea. He sought out the work site's manager and asked to borrow an air monitoring device. Reluctantly, the site manager loaned the foreman a portable air monitoring device. Armed with the air monitor, the foreman went back to the tank and informed his crew that he was going to test the inside atmosphere for contaminants. This is where the first problem arose. The foreman had never used an air monitor before. He did not know how to use it or how to calibrate it.

After about 20 minutes of frustration due to not being able to get the air monitor to function, the foreman gave up trying. Instead, he directed two of his crew members to enter the tank and determine what equipment would be needed to begin the preservation project. Fifteen minutes after the two crew members entered the tank, the foreman decided to find out how they were progressing. He walked over to the tank, stuck his head into the entry port, and asked how was it going?

There was no answer.

The foreman asked again.

No answer.

At this point, the foreman became concerned; in fact, he panicked. Without thinking too clearly, he grabbed a flashlight and entered the tank. What exactly happened then is unclear. One point is very clear, however. The next morning one of the construction officials showed up at the plant site to see how his crew was doing on the tank job. The construction official knew his men were on the job because the company truck was parked next to the tank.

The construction official could not locate his crew. He then decided that they must be working inside the tank. When he looked inside the tank he saw the dim light of a flashlight that was shining on three prostate bodies. His crew was either taking a nap or worse. It had to be worse, he reasoned—because no one could be napping in an environment that smelled that bad. The construction official feared the worse and ran into the site office to call 911. Later that day, the results were known: three dead workers.

From the case study it can be seen that there are lessons to be learned. In the first place, no company official should loan safety equipment to an outside contractor or to any other non-company person. When you loan your equipment you may also assume liability for whatever occurs. In this case, the loaning of plant equipment was the wrong thing to do. Additionally, when the site official did not show the foreman

how to operate and calibrate the air monitor, he assumed liability for the foreman's actions; he bought into the incident and its consequences. In the second place, the construction crew had not been trained on proper confined space entry procedures. If they had been properly trained, OSHA would not have been there to investigate, and, more importantly, this incident might not have occurred; the crew would still be alive.

10.4.3.5.3 Tripod and Winch, Lifeline, and Safety Harness Systems

The Confined Space Entry Standard states that whenever a person enters a vertical permit-required confined space of more than 5 feet in depth, a mechanical lifting device must be available for rescue purposes. Having the correct safety equipment on hand is not only a matter of compliance; it could literally save workers' lives. *Workers'* is stressed here in the plural because experience has shown, as the previous case study clearly pointed out, that fatalities involved with confined space entry generally involve more than one victim. Several different types of mechanical lifting devices are available for rescue purposes. Moreover, the standard portable tripod and winch system used for retrieval is available from several different manufacturers. The portable tripod and winch system used for confined space rescue must be equipped with a heavy-duty lifeline capable of retrieving personnel quickly and safely. Along with lifting mechanisms and heavy-duty lifelines, an approved safety harness must be used. Safety harnesses are particularly valuable when rescuing a helpless or unconscious victim from a confined space. The safety harness allows for safe and quick retrieval in an emergency.

10.4.3.5.4 Confined Space Ventilation Systems

When it comes to air quality, OSHA recognizes that all confined spaces can present significant dangers. Handling such situations first involves a careful analysis of the hazards, usually through use of air-monitoring equipment. There is another way to determine whether or not a particular confined space is hazardous: historical records. Confined space entry permits are generally kept on file for at least one year. Some safety professionals recommend that confined space permits that have recorded instances of hazardous conditions should be kept on file for longer periods. This is a good idea. If a confined space demonstrates that hazards have been present in the past, what is to say that they will not always be present? By compiling data from previous confined space entries, the qualified/competent person will be alerted to the hazards that are possible or probable in the confined space that he or she is attempting to enter. Whether or not a confined space has a record of hazardous conditions, it is important to remember that proper air monitoring procedures must be followed no matter what.

In most cases, an atmospheric hazard can be eliminated or reduced by ventilating the space. Ventilating confined spaces can be accomplished through the use of portable blowers. The blower should be used outside the space to be ventilated. Supply and exhaust ducting should be attached to a blower, and the ducting is lowered into the vertical or pushed into a horizontal entry confined space to ventilate. Sometimes the use of ducting can be difficult and dangerous. Bulky ventilation ducts can compromise safety by restricting worker access to confined spaces. Special ducting attachments have been designed (e.g., the saddle vent) that save time and increase

safety. The industrial saddle vent is ideal for wastewater work because it allows for ample airflow, yet takes up only 3 inches of manhole clearance, allowing for easy entries and exits.

10.4.3.5.5 Portable Lighting Equipment

With the exception of deep pumping station wetwells and some manholes that open into lengthy sewer networks, there are few environments that are more foreboding or darker than that of the inside of an underground, seemingly endless 60-inch-diameter sewer interceptor line. Because flammable/explosive gases or vapors might be present in such an environment, vapor- and explosion-proof confined space hand lamps and ground-fault protection are required. Along with using approved incandescent or fluorescent hand lamps, flashlights are often used in confined spaces. Flashlights used in confined spaces should be the approved gas-proof type. Ordinary flashlights are dangerous because they could provide the ignition source to ignite gases and vapors.

10.4.3.5.6 Nonsparking Tools

OSHA has specific requirements regarding the use of tools in flammable vapor and combustible residue areas (e.g., some confined spaces). In order to comply with OSHA and to ensure worker safety, the use of non-sparking tools is recommended. Tools made of beryllium and copper eliminate the threat of dangerous sparks.

10.4.3.5.7 Warning Signs and Barricades

The last thing confined space entry personnel need is a traffic jam in or around the area in which they are trying to perform their dangerous work. When confined space entry is required, the immediate area surrounding the entry point should be properly barricaded and posted with warning signs. A simple traffic cone and hazard tape arrangement around the confined space entry port can be effective in warning personnel about the hazard. If it is impossible to erect some type of safety barricade around the confined space area, then it may be necessary to station personnel in the exclusion area to direct traffic away from or around the space. Whichever type of barricade and warning system that is used to protect workers and the public from the confined space, it is important to leave the traffic control and warning devices in place until the work is completed.

10.4.3.5.8 Emergency Eyewash/Showers

According to the American National Standards Institute (ANSI), emergency eyewash stations and showers must be installed within 10 seconds or 100 feet of acid or corrosive hazards. Wastewater treatment facilities usually employ the use of several different acids or corrosives for various purposes. One of the most frequently used corrosive chemicals at wastewater treatment plants is NaOH (sodium hydroxide or caustic). Caustic is used in pH and odor control and other applications. Workers who work on caustic systems need to be aware of the dangers associated with caustic, the proper spill cleanup procedures, and the locations of emergency equipment such as emergency eyewash stations and showers (this information can be obtained from the MSDS for caustic). The emergency eyewash and showers must be clearly labeled.

The results of safety audits performed by the author at various wastewater treatment plants commonly indicated, surprisingly, that several emergency eyewash and shower stations were inoperable. Obviously, these inoperable stations were appropriately listed as major discrepancies in the safety audit reports. Maintaining safety equipment in an operable condition is critical to protecting the worker. Equipment such as emergency eyewash and shower stations is sometimes ignored and only becomes necessary when an accident occurs. Thus, although they are important safety devices, they are often abused through lack of maintenance, inspection, and operation. To prevent emergency eyewash stations and showers from deteriorating to the point of not being available for emergency use when needed, it is necessary to routinely inspect, test, and repair them. An eyewash inspection tag is often used at wastewater treatment facilities. This eyewash inspection tag is attached to each emergency eyewash station and shower at a treatment facility. The eyewash inspection tag is dated for the current year and lists each month of the year. Inspection of each eyewash station or shower is required on a monthly basis. That the inspection took place is documented by using a hole-punch device or some other device to indicate on the tag that the station was inspected for the particular month designated. Some wastewater treatment plants employ planned preventive maintenance (PM) programs at their facilities. This particular program has proven to be quite effective. Inspection of emergency eyewash and shower systems are items that can be easily added to the plant's PM system. Actual PM practice as just described is quite effective in ensuring that the equipment is kept operational and ready for use in emergency situations.

10.4.3.5.9 Ladder Safety

Based on safety audits that the author has conducted throughout the United States at wastewater treatment and stabilization pond facilities where pond workers were observed using ladders to enter empty ponds to perform cleanup or maintenance, a short discussion on ladder use and safety seems necessary. Choosing the right ladder for the job is an important part of working safely. Whether for maintenance or for operational reasons, ladders are devices that are used extensively in wastewater treatment. To use ladders safely, the ladders must be sturdy and in good repair. Just as inoperable eyewash stations and showers have been found during treatment plant safety audits, such audits normally uncover defective ladders that are unsafe for use. Ladders are generally ignored until they are needed. When workers determine that they need a ladder, they generally will grab the first ladder available and use it. Unfortunately, there is no guarantee that the ladder that they have chosen to use is safe. If the plant site does not have an effective ladder inspection program, it is likely that unsafe ladders will be available for workers to use.

The use of ladder inspection tags (similar to those for eyewash station and shower inspections) is prudent management action. During regularly scheduled safety audits, each plant ladder should be inspected and each ladder inspection tag should be in place with evidence that a current inspection has been conducted. Facilities where this tag and safety audit procedure has been used have found it to be very effective. The important point is that organized ladder and eyewash station and shower inspections help to ensure that such equipment is ready for use when it is needed.

10.4.3.5.10 *Miscellaneous Safety Equipment*

Several other safety devices or safety equipment should be made available to plant workers. For example, first-aid and chemical burn kits should be mounted or placed within close reach for easy access by all employees. These emergency kits must also be inspected frequently to ensure that they are properly stocked with required first-aid supplies such as bandages, dressings, splints, etc. These kits are items that can be added to the plant's PM system. Emergency response storage lockers must be properly stocked with essential items such as flashlights, helmets, blankets, tools, emergency provisions, first-aid supplies, ladders, chainsaws, extra batteries, and other devices. Emergency response storage lockers should be inventoried on a routine basis. As part of the plant safety audit these items should be spot checked to make sure they are properly stocked with needed provisions and tools. Whenever an emergency locker of any type is put together on the plant site it is a good idea to place an inventory list on the access door to the locker. With an accessible inventory list of what is required to be stored within the locker, it is easy to spot check to ensure that required materials are actually in place.

Routinely scheduled safety audits of all plant safety equipment ensure that vital equipment is available and in good working order when it is needed. In addition, as with anything else related to safety, training is important. The managers of a plant can purchase all the safety equipment they might ever have a need for and feel like the plant is safe. However, unless supervisors and workers are trained properly on the correct use of the safety equipment, a minor emergency situation could turn into a disaster.

Even if your plant uses state-of-the-art, OSHA-approved, very expensive safety harnesses to protect workers from falls, they are worthless unless properly used. For instance, suppose that one of your work crews is to perform maintenance inside a vessel that is quite deep, 75 feet deep. The work is to begin at the top of the vessel at the opening, and the crew is to work its way down inside the vessel as each step of the work is completed. To protect workers from falling, a sophisticated hoist assembly is rigged and is inspected by an expert prior to use. Later, the crew arrives at the site and dresses out in approved safety harnesses. Upon entering the vessel, the first worker is securely attached to the fall arrest system, but there's a problem that is not immediately obvious. When the worker was attached to the hoist system, he was attached by a line that was 80 feet long. Remember, that the total fall is only 75 feet. With any luck, somebody will discover the error before the worker begins his task.

The point of the preceding example is clear. Even if the best safety equipment is purchased and used, it must be used correctly. To use their equipment correctly, workers must be trained. A properly equipped wastewater treatment facility is only as good as the workers who work in it. At a minimum a wastewater facility should have the following types of safety equipment:

- Detection equipment (for gases and oxygen deficiency)
- Respirators (self-contained breathing apparatus [SCBA] packs for oxygen deficiencies)
- Safety harnesses, lines, and hoists
- Proper protective clothing, footwear, and head gear

- Ventilation equipment
- Nonsparking tools
- Communications equipment
- Portable air blower
- Explosion-proof lanterns and other safe illumination
- Warning signs and barriers
- Emergency first-aid kits
- Proper fire extinguishers
- Eyewash and shower stations in chemical storage and laboratory areas
- Safety goggles for work in laboratories and other dangerous areas

10.5 TROUBLESHOOTING

An operator, plant manager, or engineer must have a thorough understanding of the treatment process and tests required to diagnose or troubleshoot problems affecting wastewater stabilization pond effluent quality. Troubleshooting is both a science and an art. The science is based on factual engineering, scientific data collection, and verified results. The art part is based on intuition, experience, gut feelings, logic, or an innate, almost infused knowledge that only gifted troubleshooters seem to possess. You might say that their expertise and intuition could be compared to those of Sherlock Holmes. This expertise must be brought to bear to achieve the highest level of process performance from a pond system and stay within the agency's budget. Prior to a visit to the site, the following documents should be reviewed (USEPA, 2011):

- Past inspection reports
- Discharge permit
- Discharge monitoring records (DMRs) and plant performance records for a 3-year period
- Any noncompliance correspondence to compare to plant operation records and DMRs to look for trends
- Plans and specifications to verify that they reflect current plant conditions
- Current plant records to verify that it is operating within required parameters
- Organic loading rates, surface loading rates, and aeration capacity to determine whether the ponds are organically overloaded
- O&M manual to determine if the plant is being operated within the engineers' recommendations

Once on site, the following items should be observed and reviewed:

- Plant appearance and maintenance, including weed control, dike vegetation, dike erosion and stability, fencing, and outbuilding conditions
- Individual cells, noting any floating material, such as grease, sludge, floating vegetation, or mats of blue-green algae; water depth; freeboard height; cell color; septic conditions; sludge buildup; and any other problems
- Influent and effluent flows for infiltration/inflow problems, influent septicity or odors, unusually high effluent solids, or floating material

- Plant influent and effluent parameters
- Plant O&M and equipment records
- Plant staffing for operations and maintenance
- Safety equipment and procedures
- Sampling locations, methods, frequency, and weather records

10.5.1 COMMON CAUSES OF POND EFFLUENT NONCOMPLIANCE

Pond effluent violations can be caused by organic overloading, short-circuiting, algal overgrowth conditions and pond aquatic vegetation growth, sludge accumulation and nitrification, or partial nitrification. The following sections describe some of the causes of effluent violation, troubleshooting tests and results, and possible solutions.

10.5.1.1 Organic Overload

Organic overload is normally caused by influent organic shock loads or increased organic load with no corresponding increase in treatment plant capacity. This condition causes low dissolved oxygen concentrations (<1.0 mg/L) and inhibits treatment. This can be verified by calculating the organic loading (BOD_5/day) and comparing it to design capacity. A DO test and DO profiles should be run at various times of the day to verify whether there is a continuous low-DO condition. The diagnostic troubleshooting tests will demonstrate high BOD_5 , high CBOD_5 , high soluble BOD_5 , low DO, low TSS-to- BOD_5 ratio, and high NH_3 . The immediate solution is to increase organic treatment capacity by increasing aeration. In the long term, a pretreatment program with collection system monitoring of those areas suspected of introducing high organic shock loads should be developed and implemented.

10.5.1.2 Short-Circuiting

Short-circuiting normally occurs when untreated or partially treated wastewater does not have adequate detention time in the system for complete treatment. This can be caused by temperature stratification in the cells, poor inlet or outlet design, an inadequate cell length-to-width ratio or cell shape, or poor mixing and improper aerator placement. Performing a DO profile test on an established grid system while recording both DO and temperatures in 0.3-m increments from the surface to the bottom should verify a short-circuiting condition. The operator will note variations in DO and temperature indicating temperature stratification or poor mixing. The diagnostic troubleshooting test will indicate high BOD_5 , moderate TSS, and high NH_3 levels. This condition should be verified with a microscope examination of the effluent. Possible solutions are relocating aerators, adding directional aerators or mixers, adding baffles, providing recirculation to enhance mixing, and redesigning inlet and outlet structures to include manifolds or relocating structures.

10.5.1.3 Algal Overgrowth

Algal overgrowth is prevalent in areas where there is a high number of sunny days during the year. This condition occurs predominately in the spring and summer. Long detention times, shallow pond depths (1.2 to 1.8 m), abundant nutrients, warm water, and sunshine promote algal growth. The diagnostic troubleshooting test

results indicate high pH, high BOD₅, low CBOD₅, low soluble BOD₅, high TSS, high TSS-to-BOD₅ ratio, low DO (early morning), and moderate-to-high NH₃ concentrations. During the night, algae and aerobic bacteria will utilize O₂, potentially depleting the DO in the cells prior to sunrise. Lack of O₂ will cause incomplete treatment, possibly resulting in permit violation. A DO profile test run at sunrise will normally verify a lack of O₂ in the cells. A microscopic examination of the effluent and count of the algae will confirm the overgrowth conditions.

Possible solutions include increasing the aerator running time at night. The operator may choose to reduce the aerator running time during the day, allowing the algae to concentrate on the surface of the pond cells. The high concentration of algae at the surface will reduce sunlight penetration and may slow the algal growth rate. Drawing off the effluent from variable depths below the surface will also keep the algae in the cells while allowing for the discharge of higher quality water. The addition of floating covers will block the sunlight and, with the maintenance of adequate in-cell DO levels, produce higher quality effluent. The addition of physical shade, such as greenhouse fabric suspended above the surface of the cells, or chemicals such as Aquashade®, used in accordance with USEPA instructions, may also prove effective in controlling algal growth (USEPA, 2011).

10.5.1.4 Sludge Accumulation in Ponds

Sludge will accumulate in the bottom of pond cells over years of operation. Soluble organics are released from these benthic sludges and have the largest effect on ponds in the spring of the year. Diagnostic troubleshooting test results will indicate high CBOD₅, high soluble BOD₅, low to moderate TSS, low TSS-to-BOD₅ ratio, low DO, and high NH₃ concentrations. This condition can be verified with a microscopic examination. Increasing aerator running times may offer a temporary solution. Ultimately, removal of the sludge from the bottom of the pond cells will be necessary. The operator must comply with all state and federal regulations and must take care to protect the pond liner during the process.

10.5.1.5 Nitrification or Partial Nitrification

Nitrification in ponds will occur under proper environmental conditions (in warmer water temperatures and adequate DO) and is most prevalent in late spring and summer. Complete nitrification would be indicated by low BOD₅, low CBOD₅, low to moderate TSS, moderate DO, low NH₃ and moderate NO₃ levels. Partial nitrification is common in ponds in late spring and summer when adequate DO levels are not maintained for complete treatment. Troubleshooting diagnostic tests will show high BOD₅, low CBOD₅, low soluble BOD₅, low to moderate TSS, low TSS-to-BOD₅ ratio, low DO, and moderate NH₃ concentrations. Increased aeration (aerator running times) or, in some cases, increased aeration capacity may increase nitrification.

10.5.1.6 Aquatic Vegetation

Aquatic vegetation in wastewater stabilization ponds must be properly controlled; otherwise, it can provide food and cover for burrowing animals, cause short-circuiting, and prevent wave action. Roots may also penetrate pond liners and seals.

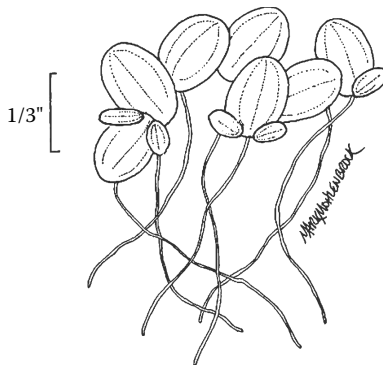


FIGURE 10.3 Common duckweed (*Lemna minor*). (From USDA, *Wetland Flora: Field Office Illustrated Guide to Plant Species*, U.S. Department of Agriculture, Washington, DC, 2013.)

Moreover, dike vegetation reduces wind action on ponds and provides nesting places for animals. Rooted weeds can be controlled by physical removal of new growth by hand, by mowing with a sickle bar after ice has formed, or by raising water level enough that ice pulls the weeds out. Also, increasing the water level to reduce light penetration will stop photosynthesis. Other possible solutions are to lower the water level and burn the weeds or use an approved herbicide.

Common duckweed (*Lemna minor*), or water lens, is a very simple flowering aquatic plant that floats on or just beneath the pond surface (see Figure 10.3). Duckweed must be physically removed with a rake, pushboard, or broom. With sufficient wind, the duckweed will be pushed to one side or corner of a pond. This is an ideal time to rake it out. It is important that duckweed not be allowed to become too abundant, as it reduces oxygen transfer at the water surface, reduces light penetration and photosynthesis, and upon decomposing can cause both odor and BOD problems.

Floating mats on pond systems are caused by floating sludge, blue-green algae, or oil and grease. The most common are the sludge and algae mats. The first step toward correcting this would be to try to break up the sludge or algae mats, allowing them to settle to the bottom. If this does not work, it will be necessary to rake them out and dispose of them. If oil and grease are a problem, the source of this material should be eliminated to prevent a recurrence of this problem (USEPA, 2011).

Cattails (*Typha latifolia*) are pond plants with a unique flowering spike and flat, blade-like leaves that reach heights of 3 to 10 feet (see Figure 10.4). They can become established in the shallow water along the dikes. Controlling cattails is a problem because of their extensive root systems. Physical removal has the potential to damage the pond liner. When cattails are young, pulling them out is very effective. Another effective method is to lower the pond level, cut the cattails, and then raise the water three feet over the cattails which effectively kills (drowns) them. A boat-mounted weed cutter can be used to cut them off below the waterline (USEPA, 2011).

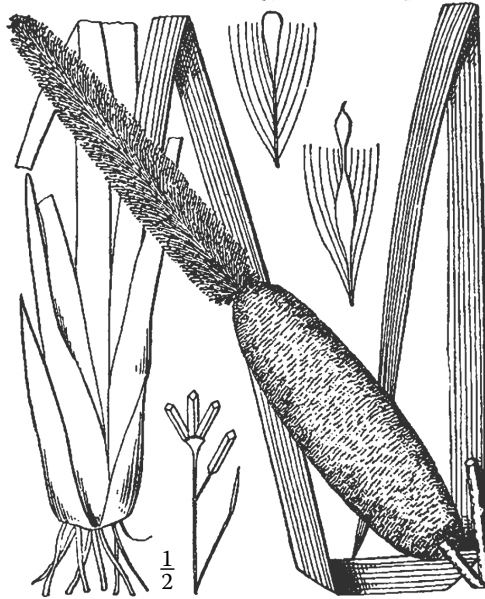


FIGURE 10.4 Broadleaf cattail (*Typha latifolia*). (From Britton, N.L. and Brown, A., (1913). *An Illustrated Flora of the Northern United States, Canada and British Possessions*, Charles Scribner's Sons, New York, 1913.)

It is very important that dikes have a protective grass cover to prevent erosion from runoff and wave action. The grasses used should be fast growing and spreading, with shallow but dense root systems (e.g., rye, brome, quack). Mowing should be done periodically so the dikes can be observed and to reduce breeding areas for insects. No long-rooted plants should be allowed on dikes (alfalfa, willows, or any wood scrubs), as their root structure could cause dike leakage, damage to the pond seal, or structural failure to the dike. All woody plants should be removed by pulling or mowing, but if they become established it will be necessary to use brushing methods (e.g., pruning, chainsaw, brushsaw, weed wacker). Grazing animals should not be used to control dike vegetation, as they damage dikes and increase erosion problems.

10.5.2 TROUBLESHOOTING CHARTS

See Table 10.4.

TABLE 10.4
Common Problems in Wastewater Treatment Pond Operations

Indicators/Observations	Probable Cause	Solutions
Odors	Organic overload	Increase aeration capacity.
	Poor aeration or mixing	After aerator run time, change or supplement type of aeration.
	Previous ice-covered ponds	Increase aerator run time. Change type of aerator to eliminate ice cover.
	Duckweed growth	Increase aerator run time. Provide chemical treatment (Diquat) or physical removal (harvest). Add ducks or geese.
	Excess weed growth on pond banks harboring flies and mosquitoes and trapping grease and organics	Physically remove the weeds by pulling, mowing, burning, or chemical treatment (Diquat). In winter, lower the pond level and allow ice to freeze around weed stems, then increase the water level.
Poor BOD removal	Organic overloading	Increase aeration capacity.
	Short-circuiting	Improve inlet–outlet conditions. Add baffles. Add recirculation to improve mixing. Add or improve aeration of ponds.
	Ice-covered ponds	Change or add aerator.
	Recent reduction in pond temperature	Increase hydraulic detention time.
	Algal bloom	Increase mechanical mixing. Add physical shade (Aquashade, Photoblu). Add floating cover such as a swimming pool cover, Styrofoam sheets, or balls. Add duckweed cover. Add an algal predator such as <i>Daphnia</i> . Add chemicals (e.g., copper sulfate). Construct wetlands to polish effluent.
High effluent TSS	Algal bloom	See algal bloom solution above.
	Excess pond mixing or short-circuiting	See short-circuiting solution above.
	Spring or fall turnover	Add different types of aeration to eliminate stratification or add supplemental aeration. Add recirculation.
	Excessive solids buildup in bottom of ponds	Physically remove solids by pumping or sludge barge; carry out proper sludge disposal in conformance with state and federal regulations.

TABLE 10.4 (cont.)
Common Problems in Wastewater Treatment Pond Operations

Indicators/Observations	Probable Cause	Solutions
Poor fecal coliform removal	Chlorine residual too low or poor chlorine contact chamber design	Increase chlorine feed rate; provide 40:1 L:W ratio. Provide a minimum 30-minute detention time at peak flow.
	Increase in chlorine-demanding substance in effluent (e.g., H ₂ S, NO ₂)	Remove solids from chlorine contact chamber. Increase chlorine feed rate.
	Water fowl contamination	Increase chlorine feed rate.
High pH	Algal stripping of carbon dioxide and bicarbonate alkalinity	See algal bloom solution above.
Low pH	Accumulation of organic sludge stuck in the "acid phase"	Physically remove sludge by pumping or sludge dredge
	Extensive nitrification	Increase aerator run time; add recirculation.
	Organic overloading	Increase aeration capacity; add recirculation.
Weeds provide cover for burrowing animals, cause short-circuiting problems, stop wave action so scum can collect, and make a nice home for mosquitoes. Also, odors can develop in the still areas. Duckweed stops sunlight penetration and prevents wind action, thus reducing the oxygen in the pond. Root penetration causes leaks in the pond seal.	Excessive <i>Daphnia</i> growth	Increase aeration capacity or run time.
	Poor circulation, maintenance, insufficient water depth	Pull weeds by hand if new growth. Mow weeds with a sickle bar mower.
		Lower the water level to expose weeds, then burn with a gas burner (check with local fire department prior to burning). After allowing the surface to freeze at a low water level, raise the water level so the floating ice will pull the weeds as it rises. (Large clumps of roots will leave holes in pond bottom, so the best results are obtained when weeds are young.) Increase water depth to above tops of weeds. Use riprap. <i>Caution:</i> If weeds get started in the riprap they will be difficult to remove but can be sprayed with USEPA-approved herbicides. To control duckweed, use rakes or push a board with a boat, then physically remove duckweed from the pond.

Burrowing animals must be controlled because of the damage they do to the dikes. Rodents such as muskrats and nutria dig partially submerged tunnels into dikes. If the water level is raised, they will burrow further and may go on out the top, thus weakening the dike.	Bank conditions that attract animals; high population in area adjacent to pond	Remove food supply such as cattails and burr reed from ponds and adjacent areas. Muskrats prefer a partially submerged tunnel; if the water level is raised, they will extend the tunnel upward, and if it is lowered sufficiently they may abandon the tunnel completely. They may be discouraged by raising and lowering the water level 6 to 8 inches over several weeks. If the problem persists, check with local game commission officers for approved methods of removal, such as live trapping.
High weed growth, brush, trees, and other vegetation provide nesting places for animals. This can cause weakening of the dike and presents an unsightly appearance. Such growth may also may reduce wind action on the pond.	Poor maintenance	Periodic mowing is the best method. Sow dikes with a mixture of fescue and bluegrass on the shore and short native grasses elsewhere. It is desirable to select a grass that will form a good sod and drive out tall weeds by binding the soil and "out competing" undesirable growth. Spray with approved weed-control chemicals. (<i>Note:</i> Be sure to check with authorities, as some states do not allow chemical usage, and all others require that chemicals be biodegradable.) Some small animals, such as sheep, have been used, but their use may increase fecal coliform levels, especially to the discharge cell. This approach is not recommended with pond systems utilizing a synthetic pond liner. Practice "rotation grazing" to prevent destroying individual species of grasses. An example schedule for rotation grazing in a three-pond system would be to graze each pond area for 2 months over a 6-month grazing season.
It is necessary to control scum formations to prevent odor problems and to eliminate breeding spots for mosquitoes. Also sizeable floating rafts will reduce sunlight.	Pond bottom turning over with sludge floating to the surface; poor circulation and wind action; high amounts of grease and oil in influent causing scum	Use rakes or a portable pump to create a water jet, or use motor boats to break up scum formations. Broken scum usually sinks. Any remaining scum should be skimmed and disposed of by burial or hauled to a landfill with the approval of regulatory agencies.

TABLE 10.4 (cont.)
Common Problems in Wastewater Treatment Pond Operations

Indicators/Observations	Probable Cause	Solutions
Low pH (less than 6.5) and dissolved oxygen (less than 1 mg/L), with foul odors when algae die off.	Blue-green algae	Apply chemical such as sodium nitrate at an application rate of 5 to 15% sodium nitrate per pound of BOD on a pound-for-pound basis. Or, apply 200 lb sodium nitrate per million gallons. Repeat at a reduced rate on succeeding days. Or, use 100 lb sodium nitrate per acre (112 kg/ha) for the first day, then 50 lb per acre (56 kg/ha) per day thereafter if odors persist. Apply in the wake of a motor boat. Install supplementary aeration such as floating aerators, caged aerators, or diffused aeration to provide mixing and oxygen. Daily trips over the pond area in a motor boat also helps. (Note: Stirring the pond may cause odors to be worse for short periods but will reduce the total length of the odorous period.) Recirculate the pond effluent to the pond influent to provide additional oxygen and to distribute the liquids concentration. Recirculate on a 1-6-ratio. Eliminate septic or high-strength industrial wastes. Keep pond clear of weeds and allow wave action on the bank to prevent mosquitoes from hatching out. (Note: <i>Gambusia</i> do not eat mosquito larvae any faster than other small fish species). Keep pond free from scum. Spray with USEPA-approved larvicide as a last resort; check with regulatory officials for approved chemicals.
Insects present in area and larvae or insects present in pond water.	Poor circulation and maintenance	Refer to common causes of pond effluent noncompliance. Warning: Prior to using copper sulfate, read the following information. Apply three applications of a solution of copper sulfate. If the total alkalinity is above 50 mg/L, apply 1200 kg/m ³ (10 lb/MG) of copper sulfate per million gallons in cell. If alkalinity is below 50 mg/L, reduce the amount of copper sulfate to 600 kg/m ³ (5 lb/MG). (Note: Some states do not approve the use of copper sulfate because in concentrations greater than 1 mg/L it is toxic to certain organisms and fish.) Break up algal blooms by motor boat or a
Blue-green algae	Incomplete treatment, overloading, poor nutrient balance	

portable pump and hose. Motor boat motors should be air cooled as algae may plug up water-cooled motors. *Important:* In the past copper sulfate has been used to control algae. It is recommended that operators check with regulatory agencies to determine if a copper parameter must be added to the discharge permit. It should also be noted that prolonged use of copper sulfate may cause a buildup of copper in the benthic sludges, making it difficult to dispose of the sludges when pond cleaning becomes necessary. Draw off effluent from below the surface by use of a good baffling arrangement or variable depth draw-off. Use multiple ponds in series. In some cases, alum dosages of 20 mg/L have been used in final cells for intermittent discharge to improve effluent quality. Dosages at or below this level are not toxic.

Correct by increasing the loading by reducing the number of cells in use.

Use series operation.

Bypass the cell and let it rest. Use parallel operation. Apply recirculation of pond effluent. Look at possible short-circuiting. Install supplementary aeration equipment.

Bypass the cell and let it rest. Use parallel operation. Apply recirculation of pond effluent. Check for possible short circuiting. Install supplementary aeration equipment if problem is persistent and due to overloading. Look for possible toxic or external causes of algae die-off and correct at source.

Increase aerator running time. Remove weeds such as duckweed if they are covering more than 40% of the pond. Reduce organic loading to primary cells by going to parallel operation. Add supplemental aeration (e.g., surface aerators, diffusers, daily operation of a motor boat). Add recirculation by using a portable pump to return final effluent to the head works. Apply sodium nitrate. Determine if overload is due to an industrial source and remove it.

Weather or temperature conditions that favor particular populations of algae

Overdesign; low seasonal flow

Short-circuiting, industrial wastes, poor design, infiltration, new construction (service area expansion), inadequate treatment, weather conditions

Overloading, long periods of adverse weather, higher animals (e.g., *Daphnia*) feeding on the algae

Poor light penetration, low detention time, high BOD loading or toxic industrial wastes

Algae-derived suspended solids present

Lightly loaded ponds

Overloading

Decreasing trend in pH followed by drop in DO as green algae die off

Low dissolved oxygen (daytime DO should drop below 1 mg/L during warm months)

TABLE 10.4 (cont.)
Common Problems in Wastewater Treatment Pond Operations

Indicators/Observations	Probable Cause	Solutions
Short-circuiting	Poor wind action due to trees or poor arrangement of inlet and outlet locations; shape of pond; weed growth; irregular bottom	Cut trees and growth at least 150 m (500 ft) away from pond if in direction of prevailing wind. Install baffling around inlet location to improve distribution. Add recirculation to improve mixing. Provide new inlet-outlet locations, including multiple inlets and manifolds. Clean out weeds. Fill in irregular bottoms. Add directional surface mixers or aerators to mix and retard flow.
Anaerobic conditions	Overloading, short-circuiting, poor operation, toxic discharge	Change from a series to parallel operation to divide load (helpful if conditions exist at a certain time each year and are not persistent). Add supplemental aeration if the pond is continuously overloaded. Change inlets and outlets to eliminate short-circuiting. Add recirculation (temporary-use portable pumps) to provide oxygen and mixing. In some cases, temporary help can be obtained by adding sodium nitrate. Eliminate the sources of toxic discharges.
Fluctuating dissolved oxygen, fine pin floc in final cell effluent, frothing and foaming, ice interfering with operation in aerated ponds	Shock loading, overaeration, industrial wastes, floating ice	Control aeration system by using a time clock to allow operation during high-load periods, monitor dissolved oxygen to set up a schedule for even operation, holding approximately 1 mg/L or more. Vary operation of aeration system to obtain solids that flocculate or clump together in the secondary cell but are not torn apart by excessive aeration. Locate industrial wastes that may cause foaming or frothing and eliminate or pretreat wastes. Examples are slaughterhouse, milk, or some vegetable wastes. Operate units continuously during cold weather to prevent freezing damage or remove completely if not a type that will prevent freeze-up.

High BOD in effluent	Short detention times, poor inlet and outlet placement, high organic or hydraulic loads, possible toxic compounds	Refer to Section 10.5.1. Check for collection system infiltration and eliminate at source. Use portable pumps to recirculate the water. Add new inlet and outlet locations. Reduce loads due to industrial sources if above design level. Prevent toxic discharges.
Odors in anaerobic ponds	Lack of cover over water surface and insufficient load to have complete activity, eventually leading to formation of a scum blanket	Use straw cast over the surface or polystyrene as a temporary cover until a good surface sludge blanket has formed.
Low pH in anaerobic ponds	Acid formers working faster than methane formers in an acid condition	Raise the pH by adding a lime slurry of 580 kg dehydrated lime per 200 L water (100 lb/50 gal) at a dosage rate of 12 g/10,000 L (1 lb/10,000 gal) in the pond. The slurry should be mixed while being added. The best place to put in the lime is at the entrance to the lagoon so it is well mixed as it enters the pond.

Source: Adapted from Richard and Bowman (1991), Spellman (2013), and USEPA (1977, 2011).

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Glossary

Absorption: Any process where one substance penetrates the interior of another substance.

Acid: Water with a pH less than 5.5; in common usage, acidic water has a pH less than 7.

Acid rain: Precipitation with higher than normal acidity, caused primarily by sulfur and nitrogen dioxide air pollution.

Acidic deposition: The transfer of acidic or acidifying substances from the atmosphere to the surface of the Earth or to objects on its surface. Transfer can be either by wet deposition (rain, snow, dew, fog, frost, hail) or by dry deposition (gases, aerosols, or fine to coarse particles).

Acre-foot (ac-ft): The volume of water needed to cover an acre of land to a depth of 1 foot; equivalent to 43,560 cubic feet or 32,851 gallons.

Activated carbon: A very porous material that, after being subjected to intense heat to drive off impurities, can be used to adsorb pollutants from water.

Activated sludge: A secondary wastewater treatment process that removes organic matter by mixing air and recycled sludge bacteria with sewage to promote decomposition.

Adsorption: The process by which one substance is attracted to and adheres to the surface of another substance, without actually penetrating its internal structure.

Advanced primary treatment: Waste treatment process that incorporates primary sedimentation of suspended solids with chemical addition and flocculation to increase the overall removal of organic solids. Advanced primary treatment typically achieves about 50% removal of suspended solids and BOD.

Advanced secondary treatment: Biological or chemical treatment processes that include a conventional activated sludge to increase the removal of solids and BOD. Typical removal rates for advanced secondary plants are on the order of 90% removal of solids and BOD.

Advanced wastewater treatment (AWT): Wastewater treatment process that includes combinations of physical and chemical operations designed to remove nutrients, toxic substances, or other pollutants. Advanced, or tertiary, treatment processes treat effluent from secondary treatment facilities using processes such as nutrient removal (nitrification, denitrification), filtration, or carbon adsorption. Tertiary treatment plants typically achieve about 95% removal of solids and BOD in addition to removal of nutrients or other materials.

Aerated pond: A wastewater treatment pond in which mechanical or diffused-air aeration is used to supplement the oxygen supply.

Aeration: A physical treatment method that promotes biological degradation of organic matter. The process may be passive (when waste is exposed to air) or active (when a mixing or bubbling device introduces the air).

- Aerobic:** Environmental conditions characterized by the presence of dissolved oxygen; term used to describe biological or chemical processes that occur in the presence of oxygen.
- Aerobic bacteria:** A type of bacteria that requires free oxygen to carry out metabolic function.
- Aerobic stabilization:** The stabilization of organic matter through metabolism into more complex matter by bacteria in the presence of dissolved oxygen.
- Algae:** Chlorophyll-bearing, nonvascular, primarily aquatic species that have no true roots, stems, or leaves; most algae are microscopic, but some species can be as large as vascular plants.
- Algal bloom:** The rapid proliferation of passively floating, simple plant life, such as blue-green algae, in and on a body of water.
- Algicide:** Any substance or chemical applied to kill or control algal growths.
- Alkaline:** Water with a pH greater than 7; in common usage, a pH of water greater than 7.4.
- Alluvial aquifer:** A water-bearing deposit of unconsolidated material (sand and gravel) left behind by a river or other flowing water.
- Alluvium:** General term for sediments of gravel, sand, silt clay, or other particulate rock material deposited by flowing water, usually in the beds of rivers and streams, on a flood plain, on a delta, or at the base of a mountain.
- Alpine snow glade:** A marshy clearing between slopes above the timberline in mountains.
- Amalgamation:** The dissolving or blending of a metal (commonly gold and silver) in mercury to separate it from its parent material.
- Ambient water quality:** Natural concentration of water quality constituents prior to mixing of either a point or non-point source load of contaminants. Reference ambient concentrations are used to indicate the concentration of a chemical that will not cause an adverse impact on human health.
- Ammonia:** A compound of nitrogen and hydrogen (NH_3) that is a common byproduct of animal waste. Ammonia readily converts to nitrate in soils and streams.
- Ammonia toxicity:** Under specific conditions of temperature and pH, the un-ionized component of ammonia can be toxic to aquatic life. The un-ionized component of ammonia increases with pH and temperature.
- Anadromous fish:** Migratory species that are born in freshwater, live mostly in estuaries and ocean water, and return to freshwater to spawn.
- Anaerobic:** Pertaining to, taking place in, or caused by the absence of oxygen.
- Anaerobic bacteria:** Bacteria that grow in the absence of free dissolved oxygen and must obtain their oxygen by chemically breaking down organic compounds containing combined oxygen.
- Anaerobic decomposition:** The breakdown of complex organic matter by bacteria in the absence of dissolved oxygen.
- Anomalies:** As related to fish, externally visible skin or subcutaneous disorders, including deformities, eroded fins, lesions, and tumors.
- Anoxic:** Aquatic environment conditions containing zero or little dissolved oxygen.
- Anthropogenic:** Having to do with or caused by humans, particularly as pertains to human influence on the environment.

- Anticline:** A fold in the Earth's crust, convex upward, whose core contains stratigraphically older rocks.
- Aquaculture:** The science of farming organisms that live in water, such as fish, shellfish, and algae.
- Aquatic:** Living or growing in or on water.
- Aquatic guidelines:** Specific levels of water quality which, if reached, may adversely affect aquatic life. These are nonenforceable guidelines issued by a governmental agency or other institution.
- Aquatic vegetation:** Vegetation that grows in or near water.
- Aquifer:** A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to springs and wells.
- Arroyo:** A small, deep, flat-floored channel or gully of an ephemeral or intermittent stream, usually with nearly vertical banks cut into unconsolidated material.
- Artificial recharge:** Augmentation of natural replenishment of groundwater storage by some method of construction, spreading of water, or pumping water directly into an aquifer.
- Assimilative capacity:** The amount of contaminant load (expressed as mass per unit time) that can be discharged to a specific stream or river without exceeding water quality standards or criteria. Assimilative capacity is used to define the ability of a water body to naturally absorb and use waste matter and organic materials without impairing water quality or harming aquatic life.
- Atmospheric deposition:** The transfer of substances from the air to the surface of the Earth, either in wet form (rain, fog, snow, dew, frost, hail) or in dry form (gases, aerosols, particles).
- Atmospheric pressure:** The pressure exerted by the atmosphere on any surface beneath or within it; equal to 14.7 pounds per square inch at sea level.
- Average discharge:** As used by the U.S. Geological Survey, the arithmetic average of all complete water years of record of surface water discharge whether consecutive or not. The term "average" generally is reserved for average of record and "mean" is used for averages of shorter periods—namely, daily, monthly, or annual mean discharges.
- Background concentration:** The concentration of a substance in a particular environment that is indicative of minimal influence by human (anthropogenic) sources.
- Backwater:** A body of water in which the flow is slowed or turned back by an obstruction such as a bridge or dam, an opposing current, or the movement of the tide.
- Bacteria:** Single-celled microscopic organisms.
- Bacterial decomposition:** Breakdown by oxidation, or decay, of organic matter by heterotrophic bacteria. Bacteria use the organic carbon in organic matter as the energy source for cell synthesis.
- Bank:** The sloping ground that borders a stream and confines the water in the natural channel when the water level, or flow, is normal.
- Bank storage:** The change in the amount of water stored in an aquifer adjacent to a surface water body resulting from a change in stage of the surface water body.

- Barrier bar:** An elongate offshore ridge, submerged at least at high tide, built up by the action of waves or currents.
- Base flow:** The sustained low flow of a stream, usually groundwater inflow to the stream channel.
- Basic:** The opposite of acidic; water that has a pH greater than 7.
- Basin and range physiography:** A region characterized by a series of generally north-trending mountain ranges separated by alluvial valleys.
- Bed material:** Sediment comprising the streambed.
- Bed sediment:** The material that temporarily is stationary in the bottom of a stream or other watercourse.
- Bedload:** Sediment that moves on or near the streambed and is in almost continuous contact with the bed.
- Bedrock:** A general term used for solid rock that underlies soils or other unconsolidated material.
- Benthic:** Refers to material, especially sediment, at the bottom of an aquatic ecosystem. It can be used to describe the organisms that live on, or in, the bottom of a water body.
- Benthic invertebrates:** Insects, mollusks, crustaceans, worms, and other organisms without a backbone that live in, on, or near the bottom of lakes, streams, or oceans.
- Benthic organism:** A form of aquatic life that lives on or near the bottom of streams, lakes, or oceans.
- Berm:** The level portion of a pond at the top of the slope. A roadway is often built on the berm.
- Bioaccumulation:** The biological sequestering of a substance at a higher concentration than that at which it occurs in the surrounding environment or medium. Also, the process whereby a substance enters organisms through the gills, epithelial tissues, digestive tract, or other sources.
- Bioavailability:** The capacity of a chemical constituent to be taken up by living organisms either through physical contact or by ingestion.
- Biochemical:** Refers to chemical processes that occur inside or are mediated by living organisms.
- Biochemical process:** A process characterized by, produced by, or involving chemical reactions in living organisms.
- Biochemical oxygen demand (BOD):** The amount of oxygen required by bacteria to stabilize decomposable organic matter under aerobic conditions.
- Biodegradation:** Transformation of a substance into new compounds through biochemical reactions or the actions of microorganisms such as bacteria.
- Biological treatment:** A process that uses living organisms to bring about chemical changes.
- Biomass:** The amount of living matter, in the form of organisms, present in a particular habitat, usually expressed as weight per unit area.
- Biota:** All living organisms of an area.
- Bog:** A nutrient-poor, acidic wetland dominated by a waterlogged, spongy mat of sphagnum moss that ultimately forms a thick layer of acidic peat; generally has no inflow or outflow and is fed primarily by rain water.

- Bonded lining:** A pond lining system that is adhesively bonded 100% to the substrate, which is usually trowel-finished concrete.
- Brackish water:** Water with a salinity intermediate between seawater and freshwater (containing from 1000 to 10,000 milligrams per liter of dissolved solids).
- Breakdown product:** A compound derived by chemical, biological, or physical action upon a pesticide. The breakdown is a natural process that may result in a more toxic or a less toxic compound and a more persistent or less persistent compound.
- Breakpoint chlorination:** The addition of chlorine to water until the chlorine demand has been satisfied and free chlorine residual is available for disinfection.
- Buoyancy ratio:** A ratio obtained by dividing the net buoyancy of the closed pond cell float members of a floating roof system by the total weight of the flexible membrane used in the roof.
- Calcareous:** Refers to rocks or substances formed of calcium carbonate or magnesium carbonate by biological deposition or inorganic precipitation, or containing those minerals in sufficient quantities to effervesce when treated with cold hydrochloric acid.
- Capillary fringe:** The zone above the water table in which water is held by surface tension. Water in the capillary fringe is under a pressure less than atmospheric.
- Carbonaceous:** Pertaining to or containing organic carbon derived from plant and animal residues.
- Carbonaceous BOD:** Biochemical oxygen demand accounted for by decompositions of organic carbon derived from plant and animal residues.
- Carbonate rocks:** Rocks (such as limestone or dolostone) that are composed primarily of minerals (such as calcite and dolomite) containing a carbonate ion.
- Center pivot irrigation:** An automated sprinkler system featuring a rotating pipe or boom that supplies water to a circular area of an agricultural field through sprinkler heads or nozzles.
- Channel scour:** Erosion by flowing water and sediment on a stream channel; results in removal of mud, silt, and sand on the outside curve of a stream bend and the bed material of a stream channel.
- Channelization:** Straightening and deepening of a stream channel to permit the water to move faster or to drain a wet area for farming.
- Chemical treatment:** A process that results in the formation of a new substance or substances. The most common chemical water treatment processes include coagulation, disinfection, water softening, and filtration.
- Chlordane:** Octachlor-4,7-methanotetrahydroindane; an organochlorine insecticide no longer registered for use in the United States. Technical chlordane is a mixture in which the primary components are *cis*- and *trans*-chlordane, *cis*- and *trans*-nonachlor, and heptachlor.
- Chlorinated solvent:** A volatile organic compound containing chlorine. Some common solvents are trichloroethylene, tetrachloroethylene, and carbon tetrachloride.
- Chlorination:** The process of adding chlorine to water to kill disease-causing organisms or to act as an oxidizing agent.

- Chlorine demand:** A measure of the amount of chlorine that will combine with impurities and is therefore unavailable to act as a disinfectant.
- Chlorofluorocarbons:** A class of volatile compounds consisting of carbon, chlorine, and fluorine. Commonly called freons, they have been used in refrigeration mechanisms, as blowing agents in the fabrication of flexible and rigid foams, and, until banned from use several years ago, as propellants in spray cans.
- Chlorophyll:** A group of green photosynthetic pigments that occur primarily in the chloroplast of plant cells. The amount of chlorophyll-*a*, a specific pigment, is frequently used as measure of algal biomass in natural waters.
- Cienaga:** A marshy area where the ground is wet due to the seepage of springs.
- Clean Water Act (CWA):** Federal law enacted in 1972 (with several subsequent amendments) with the objective to restore and maintain the chemical, physical, and biological integrity of the nation's waters. Its long-range goal is to eliminate the discharge of pollutants into navigable waters and to make national waters fishable and swimmable.
- Climate:** Sum total of the meteorological elements that characterize the average and extreme conditions of the atmosphere over a long period of time at any one place or region of the Earth's surface.
- Coagulants:** Chemicals that cause small particles to stick together to form larger particles.
- Coagulation:** A chemical water treatment method that causes very small suspended particles to attract one another and form larger particles. This is accomplished by the addition of a coagulant that neutralizes the electrostatic charges that cause particles to repel each other.
- Coliform bacteria:** A group of bacteria predominantly inhabiting the intestines of humans or animals but also occasionally found elsewhere. The presence of these bacteria in water is used as an indication of fecal contamination.
- Color:** A physical characteristic of water. Color is most commonly tan or brown from oxidized iron, but contaminants may cause other colors, such as green or blue. Color differs from turbidity, which is a measure of the cloudiness of water.
- Combined sewer overflow (CSO):** A discharge of untreated sewage and stormwater to a stream when the capacity of a combined storm/sanitary sewer system is exceeded by storm runoff.
- Commercial water use:** Water used for motels, hotels, restaurants, office buildings, and other commercial operations.
- Communicable diseases:** Usually caused by microbes (microscopic organisms, such as bacteria, protozoa, and viruses). Most microbes are essential components of our environment and do not cause disease. Those that do are considered to be pathogenic organisms, or simply pathogens.
- Community:** In ecology, the species that interact in a common area.
- Community water system:** A public water system that serves at least 15 service connections used by year-round residents or regularly serves at least 25 year-round residents.
- Composite sample:** A series of individual or grab samples taken at different times from the same sampling point and mixed together.

- Concentration:** The ratio of the quantity of any substance present in a sample of a given volume or a given weight compared to the volume or weight of the sample.
- Cone of depression:** The depression of heads around a pumping well caused by withdrawal of water.
- Confined aquifer (artesian aquifer):** An aquifer that is completely filled with water under pressure and that is overlain by material that restricts the movement of water.
- Confining layer:** A body of impermeable or distinctly less permeable material stratigraphically adjacent to one or more aquifers that restricts the movement of water into and out of the aquifers.
- Confluence:** The flowing together of two or more streams; the place where a tributary joins the main stream.
- Conglomerate:** A coarse-grained sedimentary rock composed of fragments larger than 2 millimeters in diameter.
- Constituent:** A chemical or biological substance in water, sediment, or biota that can be measured by an analytical method.
- Construction Grants Program:** Federal funding authorized by amendments (1956 through 1987) to the 1948 Federal Water Pollution Control Act to provide technical assistance and construction money to aid municipalities in building and upgrading sewerage collection systems and municipal wastewater treatment plants. After the 1972 amendments, \$61.1 billion (current year dollars) in federal funding was provided under the Clean Water Act to upgrade municipal wastewater facilities to a minimum of secondary treatment.
- Consumptive use:** The quantity of water that is not available for immediate rescue because it has been evaporated, transpired, or incorporated into products, plant tissue, or animal tissue.
- Contact recreation:** Recreational activities, such as swimming and kayaking, in which contact with water is prolonged or intimate and in which there is a likelihood of ingesting water.
- Contaminant:** A toxic material found as an unwanted residue in or on a substance.
- Contamination:** Degradation of water quality compared to original or natural conditions due to human activity.
- Contributing area:** The area in a drainage basin that contributes water to stream-flow or recharge to an aquifer.
- Conventional pollutants:** As specified under the Clean Water Act, conventional contaminants include suspended solids, coliform bacteria, biochemical oxygen demand, pH, and oil and grease.
- Core sample:** A sample of rock, soil, or other material obtained by driving a hollow tube into the undisturbed medium and withdrawing it with its contained sample.
- Count:** With reference to a pond liner, the number of threads per inch in the fabric; expressed as two numbers separated by an $\times$. The first number is the number of warp yarns per inch and the second number is the number of fill (picks) yarns per inch.
- CPE:** Abbreviation for chlorinated polyethylene membrane.

Criterion: A standard rule or test on which a judgment or decision can be based.

Critical reservoir: A reservoir (or lake or pond) that could cause possible loss of life or extensive property damage if it failed. Sometimes used to designate a body of water, functional or decorative, that sits over a potable water reservoir. Also, a body of water, functional or decorative, that sits above a normally occupied area where leakage could cause inconvenience to persons or damage to property below.

Cross-connection: Any connection between safe drinking water and a nonpotable water or fluid.

Cured membranes: Pond liner materials that cure, usually by the chemical cross-linking of molecules, to yield a compound that is not softened upon subsequent exposure to heat. The curing process also renders the membrane more resistant to chemical attack.

Cut-and-fill reservoir: A reservoir constructed by excavating the central portion of the area and then utilizing the excavated material as fill material for the embankment. Even if the earth from the hole is not used in the embankment, the facility is still referred to as a cut-and-fill reservoir.

C×T value: The product of the residual disinfectant concentration (C, in milligrams per liter) and the corresponding disinfectant contact time (T, in minutes). Minimum C×T values are specified by the Surface Water Treatment Rule as a means of ensuring adequate kill or inactivation of pathogenic microorganisms in water.

Datum plane: A horizontal plane to which ground elevations or water surface elevations are referenced.

Decay: Gradual decrease in the amount of a given substance in a given system due to various loss/sink processes including chemical and biological transformation, dissipation to other environmental media, or deposition into storage areas.

Decomposition: Metabolic breakdown of organic materials; the formation of decomposition byproducts releases energy and simple organics and inorganic compounds.

Deepwater habitat: Permanently flooded lands lying below the deepwater boundary of wetlands.

Degradation products: Compounds resulting from transformation of an organic substance through chemical, photochemical, and/or biochemical reactions.

Denitrification: A process by which oxidized forms of nitrogen such as nitrate are reduced to form nitrites, nitrogen oxides, ammonia, or free nitrogen; commonly brought about by the action of denitrifying bacteria and usually resulting in the escape of nitrogen to the air.

Detection limit: The concentration of a constituent or analyte below which a particular analytical method cannot determine, with a high degree of certainty, the concentration.

Diatoms: Single-celled, colonial, or filamentous algae with siliceous cell walls constructed of two overlapping parts.

Dilution: Addition of a volume of less concentrated liquid (e.g., water) that results in a decrease in the original concentration.

- Direct runoff:** The runoff entering stream channels promptly after rainfall or snowmelt.
- Discharge:** The volume of fluid passing a point per unit of time, commonly expressed in cubic feet per second, million gallons per day, gallons per minute, or seconds per minute per day.
- Discharge area (groundwater):** Area where subsurface water is discharged to the land surface, to surface water, or to the atmosphere.
- Discharge permit (NPDES):** A permit issued by the USEPA or a state regulatory agency that sets specific limits on the type and amount of pollutants that a municipality or industry can discharge to a receiving water; also includes a compliance schedule for achieving those limits. It is known as a NPDES permit because the permit process was established under the National Pollutant Discharge Elimination System, under provisions of the Federal Clean Water Act.
- Disinfectant and disinfection byproducts (D-DBPs):** A term used in connection with state and federal regulations designed to protect public health by limiting the concentration of either disinfectants or the byproducts formed by the reaction of disinfectants with other substances in the water (such as trihalomethanes, THMs).
- Disinfection:** A chemical treatment method; the addition of a substance (e.g., chlorine, ozone hydrogen peroxide) that destroys or inactivates harmful microorganisms or inhibits their activity.
- Dispersion:** The extent to which a liquid substance introduced into a groundwater system spreads as it moves through the system.
- Dissociation:** The process of ion separation that occurs when an ionic solid is dissolved in water.
- Dissolved constituent:** A constituent that passes through a 0.45-micrometer filter.
- Dissolved oxygen (DO):** The oxygen dissolved in water; usually expressed in milligrams per liter, parts per million, or percent of saturation.
- Dissolved solids:** Any material that can dissolve in water and be recovered by evaporating the water after filtering the suspended material.
- Diurnal:** Actions or processes having a period or a cycle of approximately one tidal-day or are completed within a 24-hour period and which recur every 24 hours; having a daily cycle.
- Diversion:** A turning aside or alteration of the natural course of a flow of water, normally considered physically to leave the natural channel. In some states, this can be a consumptive use directly from another stream, such as by livestock watering. In other states, a diversion must consist of such actions as taking water through a canal, pipe, or conduit.
- Dolomite:** A sedimentary rock consisting chiefly of magnesium carbonate.
- Domestic wastewater:** Also called sanitary wastewater, it consists of wastewater discharged from residences and from commercial, institutional, and similar facilities.
- Domestic water use:** Water used for normal household purposes such as drinking, food preparation, bathing, washing clothes and dishes, watering lawns and gardens, or flushing toilets. Also called *residential water use*.

- Drainage area:** The drainage area of a stream at a specified location is the area, measured in a horizontal plane, that is enclosed by a drainage divide.
- Drainage basin:** The land area drained by a river or stream. Also referred to as *watershed*, *river basin*, or *hydrologic unit*.
- Drainage divide:** Boundary between adjoining drainage basins.
- Drawdown:** The difference between the water level in a well before pumping and the water level in the well during pumping. Also, for flowing wells, the reduction of the pressure head as a result of the discharge of water.
- Drinking water standards:** Water quality standards addressing suspended solids, unpleasant taste, and microbes harmful to human health. Drinking water standards are included in state water quality rules.
- Drinking water supply:** Any raw or finished water source that is or may be used as a public water system or as drinking water by one or more individuals.
- Drip irrigation:** An irrigation system in which water is applied directly to the root zone of plants by means of applicators (orifices, emitters, porous tubing, or perforate pipe) operated under low pressure. The applicators can be placed on or below the surface of the ground or can be suspended from supports.
- Drought:** A prolonged period of less-than-normal precipitation such that the lack of water causes a serious hydrologic imbalance.
- Dynamic model:** A mathematical formulation describing the physical behavior of a system or a process and its temporal variability.
- Dynamic simulation:** Modeling the behavior of physical, chemical, and/or biological phenomena and their variation over time.
- Ecoregion:** An area of similar climate, landform, soil, potential natural vegetation, hydrology, or other ecologically relevant variables.
- Ecosystem:** A community of organisms considered together with the nonliving factors of its environment.
- Effluent:** Outflow from a particular source, such as a stream that flows from a lake or liquid waste that flows from a factory or sewage-treatment plant.
- Effluent limitations:** Standards developed by the USEPA to define the levels of pollutants that could be discharged into surface waters.
- Electrodialysis:** The process of separating substances in a solution by dialysis, using an electric field as the driving force.
- Electronegativity:** The tendency for atoms that do not have a complete octet of electrons in their outer shell to become negatively charged.
- Emergent plants:** Erect, rooted, herbaceous plants that may be temporarily or permanently flooded at the base but do not tolerate prolonged inundation of the entire plant.
- Enforcement conferences:** Joint state and federal water pollution conferences convened by the U.S. Public Health Service under authority of the 1956 amendments to the 1948 Federal Water Pollution Control Act. Federal regulatory authority is restricted to enforcement of water pollution problems only in interstate waters because of the commerce clause of the U.S. Constitution. Fifty-one enforcement conferences were convened from 1957 to 1972.

- Enhanced Surface Water Treatment Rule (ESWTR):** A revision of the original Surface Water Treatment Rule that includes new technology and requirements to deal with newly identified problems.
- Environment:** The sum of all conditions and influences affecting the life of organisms.
- Environmental sample:** A water sample collected from an aquifer or stream for the purpose of chemical, physical, or biological characterization of the sampled resource.
- Environmental setting:** Land area characterized by a unique combination of natural and human-related factors, such as row-crop cultivation or glacial-till soils.
- Ephemeral stream:** A stream or part of a stream that flows only in direct response to precipitation; it receives little or no water from springs, melting snow, or other sources; its channel is at all times above the water table.
- EPT richness index:** An index based on the sum of the number of taxa in three insect orders—Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies)—which are composed primarily of species considered to be relatively intolerant to environmental alterations.
- Erosion:** The process whereby materials of the Earth's crust are loosened, dissolved, or worn away and simultaneously moved from one place to another.
- Estuary:** Brackish-water areas influenced by the ocean tides where the mouth of the river meets the sea.
- Eutrophication:** The process by which water becomes enriched with plant nutrients, most commonly phosphorus and nitrogen.
- Evaporite minerals (deposits):** Minerals or deposits of minerals formed by evaporation of water containing salts. These deposits are common in arid climates.
- Evaporites:** A class of sedimentary rocks composed primarily of minerals precipitated from a saline solution as a result of extensive or total evaporation of water.
- Evapotranspiration:** The process by which water is discharged to the atmosphere as a result of evaporation from the soil and surface water bodies and transpiration by plants.
- Factor of safety:** Coefficient used to account for uncertainties in representing, simulating, or designing a system.
- Facultative bacteria:** A type of anaerobic bacteria that can metabolize its food either aerobically or anaerobically.
- Fall line:** Imaginary line marking the boundary between the ancient, resistant crystalline rocks of the Piedmont province of the Appalachian Mountains and the younger, softer sediments of the Atlantic Coastal Plain province in the Eastern United States. Along rivers, this line commonly is reflected by waterfalls.
- Fecal coliform bacteria:** Microscopic single-celled organisms (primarily fecal coliforms and fecal streptococci) found in the wastes of warm-blooded animals. Their presence in water is used to assess the sanitary quality of water for body-contact recreation or for consumption. Their presence indicates contamination by the wastes of warm-blooded animals and the possible presence of pathogenic (disease-producing) organisms.

Federal Water Pollution Control Act of 1972: The Act outlines the objective “to restore and maintain the chemical, physical, and biological integrity of the nation’s waters.” This Act and subsequent Clean Water Act amendments are the most far-reaching water pollution control legislation ever enacted. They provided for comprehensive programs for water pollution control, uniform laws, and interstate cooperation, as well as grants for research, investigation, training, and information on national programs on surveillance, the effects of pollutants, pollution control, and the identification and measurement of pollutants. Additionally, they allot grants and loans for the construction of treatment works. The Act established national discharge standards with enforcement provisions and mandates a strong pretreatment program to control toxic pollutants discharged by industry into publicly owned treatment works (POTWs). The 1987 amendments require that stormwater from industrial activity must be regulated. The Federal Water Pollution Control Act established several milestone achievement dates. It required secondary treatment of domestic waste by POTWs and the application of “best practicable” water pollution control technology by 1977. Virtually all industrial sources have achieved compliance. The Act also called for new levels of technology to be imposed during the 1980s and 1990s, particularly for controlling toxic pollutants.

Fertilizer: Any of a large number of natural or synthetic materials, including manure and nitrogen, phosphorus, and potassium compounds, spread on or worked into soil to increase its fertility.

Filtrate: Liquid that has been passed through a filter.

Filtration: A physical treatment method for removing solid (particulate) matter from water by passing the water through porous media such as sand or manufactured filter materials.

Fish mouths: Separation of butyl-type cured sheets at the joint due to unequal tension between the sheets.

Flocculation: The water treatment process following coagulation; it uses gentle stirring to bring suspended particles together so they will form larger, more settleable clumps called floc.

Flood: Any relatively high streamflow that overflows the natural or artificial banks of a stream.

Flood attenuation: A weakening or reduction in the force or intensity of a flood.

Flood irrigation: The application of irrigation water whereby the entire surface of the soil is covered by ponded water.

Flood plain: A strip of relatively flat land bordering a stream channel that is inundated at times of high water.

Flow line: The idealized path followed by particles of water.

Flowpath: An underground route for groundwater movement, extending from a recharge (intake) zone to a discharge (output) zone such as a shallow stream.

Flushing characteristics: Measure of the displacement of water from a riverine or estuarine system as controlled by the combined actions of freshwater inflow and tidal mixing and exchange.

Fluvial: Pertaining to a river or stream.

Frequency analysis: A numerical determination of the distribution of values for a parameter within a dataset.

Freshwater: Water that contains less than 1000 milligrams per liter of dissolved solids.

Freshwater chronic criteria: The highest concentration of a contaminant that freshwater aquatic organisms can be exposed to for an extended period of time (4 days) without adverse effects.

Fungi: Of relatively minor importance in water/wastewater operations (except for biosolids composting, where they are critical), fungi, like bacteria, are also extremely diverse. They are multicellular, autotrophic, photosynthetic protists that grow as filamentous, mold-like forms or as yeast-like (single-celled) organisms. They feed on organic material. Aquatic fungi grow as *parasites* on living plants or animals and as *saprophytes* on those that are dead.

Gauging station: A specific location on a stream, river, canal, lake, reservoir, or pond where systematic measurements of hydrologic data such as stage height and stream flow are collected. The U.S. Geological Service (USGS) maintains and operates a network of stream gauging stations to collect hydrologic data for many streams and rivers. Historical stream flow and stage height data are available from the USGS stream flow database (<http://waterdata.usgs.gov/nwis>). Earliest records date back to the later 19th century for some rivers.

Grab sample: A single water sample collected at one time from a single point.

“Gray” literature: Unpublished technical reports and memoranda, data reports, or other documents prepared by academic researchers; federal, state, or local agencies; or other institutions and organism. Typically limited distribution makes it difficult to obtain except from agency or institutional sources.

Groundwater: Freshwater found under the Earth’s surface, usually in aquifers. Groundwater is a major source of drinking water and a source of a growing concern in areas where leaching agricultural or industrial pollutants or substances from leaking underground storage tanks are contaminating groundwater.

Habitat: The part of the physical environment in which a plant or animal lives.

Hardness: A characteristic of water caused primarily by the salts of calcium and magnesium. It causes deposition of scale in boilers, damage in some industrial processes, and sometimes objectionable taste. It may also decrease the effectiveness of soap.

Headwaters: The source and upper part of a stream.

Hydraulic conductivity: The capacity of a rock to transmit water. It is expressed as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic gradient: The change of hydraulic head per unit of distance in a given direction.

Hydraulic loading: The volume of flow per day per unit area.

Hydrogen bonding: The term used to describe the weak but effective attraction that occurs between polar covalent molecules.

Hydrograph: Graph showing the variation of water elevation, velocity, streamflow, or other property of water with respect to time.

Hydrologic accounting unit: Geographical subdivision of watersheds within each hydrologic subregion. There are 378 accounting units in the United States. Hydrologic accounting units are identified by adding a two-digit code to the hydrologic subregion code; for example, 070102 is the code for the Twin Cities area of the Upper Mississippi River.

Hydrologic cataloging unit: Geographical subdivision of watersheds within each hydrologic accounting unit. There are 2264 cataloging units in the United States. Hydraulic cataloging units are identified by adding a two-digit code to the hydrologic accounting unit code; for example, 07010206 is the code for the Twin Cities watershed.

Hydrologic cycle: Literally the water–earth cycle. The movement of water in all three physical forms through the various environmental mediums (air, water, biota, and soil).

Hydrologic region: Largest geographical subdivision of the United States into successively smaller hydrologic units based on drainage (hydraulic subregion, hydraulic accounting unit, and hydraulic cataloging unit). There are 21 hydrologic regions in the United States. Hydrologic regions are identified by a two-digit code; for example, 07 is the hydrologic region for the Upper Mississippi River basin.

Hydrologic subregion: Geographical subdivision of watersheds within each hydrologic region. There are 221 subregions in the United States. Hydrologic subregions are identified by adding a two-digit code to the hydrologic region code; for example, 0701 is the hydrologic subregion for the Mississippi headwaters of the Upper Mississippi River basin.

Hydrology: The science that deals with water as it occurs in the atmosphere, on the surface of the ground, and underground.

Hydrostatic pressure: The pressure exerted by the water at any given point in a body of water at rest.

Hygroscopic: A substance that readily absorbs moisture.

Impermeability: The incapacity of a rock to transmit a fluid.

In situ: Latin phrase for “in place”; *in situ* measurements consist of measuring components or processes in a full-scale system or in the field rather than in a laboratory.

Index of biotic integrity (IBI): An aggregated number, or index, based on several attributes or metrics of a fish community that provides an assessment of biological conditions.

Indicator sites: Stream sampling sites located at outlets of drainage basins with relatively homogeneous land use and physiographic conditions; most indicator-site basins have drainage areas ranging from 20 to 200 square miles.

Industrial water use: Water used for industrial purposes such as fabricating, processing, washing, and cooling. Industries that use water include steel, chemicals and allied products, paper and allied products, mining, and petroleum refining.

Infiltration: The downward movement of water from the atmosphere into soil or porous rock.

Influent: Water flowing into a reservoir, basin, or treatment plant.

Inorganic: Containing no carbon; matter other than plant or animal.

Inorganic chemical: A chemical substance of mineral origin not having carbon in its molecular structure.

Inorganic matter: Chemical substances of mineral origin.

Inorganic soil: Soil with less than 20% organic matter in the upper 16 inches.

Instantaneous discharge: The volume of water that passes a point at a particular instant of time.

Instream use: Water use taking place within the stream channel for such purposes as hydroelectric power generation, navigation, water-quality improvement, fish propagation, and recreation. Sometimes called *nonwithdrawal use* or *in-channel use*.

Intermittent stream: A stream that flows only when it receives water from rainfall runoff or springs, or from some surface source such as melting snow.

Internal drainage: Surface drainage whereby the water does not reach the ocean, such as drainage toward the lowermost or central part of an interior basin or closed depression.

Intertidal: Alternately flooded and exposed by tides.

Intolerant organisms: Organisms that are not adaptable to human alterations to the environment and thus decline in numbers where alterations occur.

Invertebrate: An animal having no backbone or spinal column.

Ion: A positively or negatively charged atom or group of atoms.

Ionic bond: The attractive forces between oppositely charged ions—for example, the forces between the sodium and chloride ions in a sodium chloride crystal.

Irrigation: Controlled application of water to arable land to supply the water requirements of crops not satisfied by rainfall.

Irrigation return flow: The part of irrigation applied to the surface that is not consumed by evapotranspiration or uptake by plants and that migrates to an aquifer or surface water body.

Irrigation withdrawals: Withdrawals of water for application on land to assist in the growing of crops and pastures or to maintain recreational lands.

Kill: Dutch term for stream or creek.

Lacustrine: Pertaining to, produced by, or formed in a lake.

Leachate: A liquid that has percolated through soil containing soluble substances and that contains certain amounts of these substances in solution.

Leaching: The removal of materials in solution from soil or rock; also refers to the movement of pesticides or nutrients from land surfaces to groundwater.

Limnetic: The deepwater zone (greater than 2 meters deep).

Littoral: The shallow-water zone (less than 2 meters deep).

Load: Material that is moved or carried by streams, reported as weight of material transported during a specific time period, such as tons per year.

Loading rate: The total amount of material (pollutants) entering the system from one or multiple sources; measured as a rate in weight (mass) per unit time.

Low flow ($Q_{10/7}$): The 7-day average low flow occurring once in 10 years; this probability-based statistic is used in determining stream design flow conditions and for evaluating the water quality impact of effluent discharge limits.

Main stem: The principal trunk of a river or a stream.

Margin of safety (MOS): A required component of the total maximum daily load (TMDL) that accounts for the uncertainty about the relationship between the pollutant load and the quality of the receiving water body.

Marsh: A water-saturated, poorly drained area, intermittently or permanently water covered, having aquatic and grasslike vegetation.

Mass balance: The simplest way to express the fundamental engineering principle of mass balance is, “Everything has to go somewhere.” More precisely, the law of conservation of mass says that when chemical reactions take place, matter is neither created nor destroyed. What this important concept allows us to do is track materials (e.g., pollutants, microorganisms, chemicals) from one place to another. The concept of mass balance plays an important role in treatment plant operations (especially wastewater treatment) where we assume that a balance exists between the material entering and leaving the treatment plant or a treatment process: “What comes in must equal what goes out.” The concept is very helpful in evaluating biological systems, sampling and testing procedures, and for many other unit processes within the treatment system. The mass balance for the settling tank calculates the quantity of solids entering and leaving the unit. The values for the influent and for the effluent must be within 10 to 15% of each other to be considered acceptable. Larger discrepancies may indicate sampling errors or increasing solids levels in the unit or undetected solids discharge in the tank effluent. To get a better feel for how the mass balance principle applies to settling tanks, consider the following procedure:

1. Determine pounds of influent suspended solids (solids in).
2. Determine pounds of effluent suspended solids.
3. Calculate solids out (pounds of biosolids solids pumped per day).
4. Calculate mass balance = solids in – (solids out + biosolids solids pumped).

A settling tank receives a daily flow of 4.20 MGD. The influent contains 252 mg/L suspended solids, and the unit effluent contains 140 mg/L suspended solids. The biosolids pump operates 10 min/hr and removes biosolids at the rate of 40 gpm. The biosolids are 4.2% solids. Determine if the mass balance for solids removal is within the acceptable 10 to 15% range.

1. Solids in (influent) = $252 \text{ mg/L} \times 4.20 \text{ MGD} \times 8.34 = 8827 \text{ lb/day}$
2. Solids out (effluent) = $140 \text{ mg/L} \times 4.20 \text{ MGD} \times 8.34 = 4904 \text{ lb/day}$
3. Calculate biosolids out (lb/day):

$$10 \text{ min/hr} \times 24 \text{ hr/day} \times 40 \text{ gpm} \times 8.34 \times 0.042 = 3363 \text{ lb/day}$$

4. Mass balance = $8827 \text{ lb/day} - (4904 \text{ lb/day} + 3363 \text{ lb/day}) = 560 \text{ lb}$,
or 6.3%

The amount of BOD removed by a treatment process is directly related to the quantity of solids the process will generate. Because the actual amount of solids generated will vary with operational conditions and design, exact figures must be determined on a case-by-case basis.

Mathematical model: A system of mathematical expressions that describe the spatial and temporal distribution of water quality constituents resulting from fluid transport and the one, or more, individual processes and interactions within some prototype aquatic ecosystem. A mathematical water quality model is used as the basis for waste load allocation evaluations.

Maturity (stream): The stage in the development of a stream at which it has reached its maximum efficiency, when velocity is just sufficient to carry the sediment delivered to it by tributaries; characterized by a broad, open, flat-floored valley having a moderate gradient and gentle slope.

Maximum contaminant level (MCL): The maximum allowable concentration of a contaminant in drinking water, as established by state and/or federal regulations. Primary MCLs are health related and mandatory. Secondary MCLs are related to the aesthetics of the water and are highly recommended, but not required.

Mean: The numerical average of a set of observations; computed as the sum of the observations divided by the number of observations in the dataset.

Mean discharge: The arithmetic mean of individual daily mean discharges of a stream during a specific period, usually daily, monthly, or annually.

Median (50th percentile): A middle statistic based on ranking a dataset from the minimum to the maximum value. The median value divides the dataset such that one-half of the values are lower than the median and one-half of the values are greater than the median. The median is also defined as the 50th percentile value.

Membrane filter method: A laboratory method used for coliform testing. The procedure uses an ultra-thin filter with a uniform pore size smaller than bacteria (less than a micron). After water is forced through the filter, the filter is incubated in a special medium that promotes the growth of coliform bacteria. Bacterial colonies with a green-gold sheen indicate the presence of coliform bacteria.

Method detection limit: The minimum concentration of a substance that can be accurately identified and measured with current lab technologies.

Midge: A small fly in the family Chironomidae. The larval (juvenile) life stages are aquatic.

Milligrams per liter (mg/L): A unit of measurement expressing the concentration of a constituent in solution as the weight (mass) of solute (1 milligram) per unit volume (1 liter) of water; equivalent to 1 part per million (ppm) for a water density of $\sim 1 \text{ g cm}^{-3}$. $1 \text{ mg/L} = 1000 \text{ } \mu\text{m/L}$; $1 \text{ g/L} = 1000 \text{ mg/L}$.

Million gallons per day (MGD): Rate of water volume discharge representing a volume of 1 million gallons of water passing across a given location in a time interval of 1 day. A flow rate of $1 \text{ MGD} = 1.54723 \text{ cubic feet per second (cfs)} = 0.04381 \text{ cubic meters per second (cms)}$.

Mineralization: The transformation of organic matter into a mineral or an inorganic compound.

Minimum reporting level (MRL): The smallest measured concentration of a constituent that may be reliably reported using a given analytical method. In many cases, the MRL is used when documentation for the method detection limit is not available.

Mitigation: Actions taken to avoid, reduce, or compensate for the effects of human-induced environmental damage.

Mixing characteristics: Refers to the tendency for natural waters to blend—that is, for dissolved and particulate substances to disperse into adjacent waters.

Modes of transmission of disease: The ways in which diseases spread from one person to another.

Monitoring: Repeated observation, measurement, or sampling at a site, on a scheduled or event basis, for a particular purpose.

Monitoring well: A well designed for measuring water levels and testing ground-water quality.

Most probable number (MPN): Measure of concentration, or abundance, or total and fecal coliform bacteria based on incubation results and a statistical interpretation of the results. Calculation of the MPN requires selection of a valid series of three consecutive dilutions. The number of positive tubes in each of the three selected dilution inoculations is used to determine the MPN/100 mL. When selecting the dilution inoculations to be used in the calculation, each dilution is expressed as a ratio of positive tubes per tubes inoculated in the dilution (e.g., three positive per five inoculated, or 3/5). Several rules must be followed when determining the most valid series of dilutions. In the following examples, four dilutions were used for the test.

1. Using the confirming test data, select the highest dilution showing all positive results (no lower dilution showing less than all positive) and the next two higher dilutions.
2. If a series shows all negative values with the exception of one dilution, select the series that places the only positive dilution in the middle of the selected series.
3. If a series shows a positive result in a dilution higher than the selected series (using rule 1), it should be incorporated into the highest dilution of the selected series.

After selecting the valid series, the MPN/1000 mL is determined by locating the selected series on the MPN reference chart. If the selected dilution series matches the dilution series of the reference chart, the MPN value from the chart is the reported value for the test. If the dilution series used for the test does not match the dilution series of the chart, the test result must be calculated.

$$\text{MPN/100 mL} = \text{MPN}_{\text{chart}} \times \frac{\text{Sample volume in first dilution}_{\text{chart}}}{\text{Sample volume in first dilution}_{\text{sample}}}$$

- Multiple-tube fermentation method:** A laboratory method used for coliform testing that uses a nutrient broth placed in a culture tube. Gas production indicates the presence of coliform bacteria. The multiple fermentation technique for fecal coliform testing is useful in determining the fecal coliform density in most water, solid, or semisolid samples. Wastewater testing normally requires use of the presumptive and confirming test procedures. It is recognized as the method of choice for any samples that may be controversial (enforcement related). The technique is based on the most probable number of bacteria present in a sample that produces gas in a series of fermentation tubes with various volumes of diluted sample. The MPN is obtained from charts based on statistical studies of known concentrations of bacteria. The sample dilutions are first incubated in a lauryl (sulfonate) tryptose broth for 24 to 48 hours (presumptive test). Positive samples are then transferred to EC broth and incubated for an additional 24 hours (confirming test). Positive samples from this second incubation are used to statistically determine the MPN from the appropriate reference chart. A single-media, 24-hour procedure is also acceptable. In this procedure, sample dilutions are inoculated in A-1 media and incubated for 3 hours at 35°C; they are then incubated the remaining 20 hours at 44.5°C. Positive samples from these inoculations are used to statistically determine the MPN value from the appropriate chart.
- Municipal wastewater inventory:** U.S. Public Health Service compilation of inventories of municipal wastewater plants, populations served, and influent flows for different categories of municipal wastewater treatment facilities.
- National Pollutant Discharge Elimination System (NPDES):** A requirement of the Clean Water Act that discharges must meet certain requirements prior to the waste being discharged to any water body. It sets the highest permissible effluent limits, by permit, prior to making any discharge.
- National Primary Drinking Water Regulations (NPDWRs):** Regulations developed under the Safe Drinking Water Act that establish maximum contaminant levels, monitoring requirements, and reporting procedures for contaminants in drinking water that endanger human health.
- Natural waters:** Flowing water body within a physical system that has developed without human intervention and in which natural processes continue to take place; streams, rivers, lakes, bays, estuaries, coastal areas, and the open ocean are examples of natural waters.
- Near coastal water initiative:** Developed in 1985 to provide for management of specific problems in waters near coastlines not dealt with in other programs.
- Needs Surveys:** Compiled from 1976 to 1996 at 2- to 4-year intervals, USEPA Clean Water Needs Surveys (CWNSs) document the inventory of wastewater plants, populations served, and influent flow and effluent load of BOD₅ and TSS by six different categories of municipal wastewater treatment facilities.
- 90th percentile:** A high-end statistic based on ranking a dataset from the minimum to the maximum value. The 90th percentile defines the value for which 90% of the ranked dataset is less than the statistic and 10% of the dataset is greater than the statistic. Used in this study to define “worst-case” conditions for evaluation of “before and after” trends of BOD₅.

Nitrate (NO_3) and nitrite (NO_2): Ions consisting of nitrogen and oxygen. Nitrate is a plant nutrient used by aquatic plants for photosynthesis and is very mobile in soils.

Nitrification: The first basic step in the biological process of nitrification and denitrification. In nitrification, the secondary effluent is introduced into another aeration tank, trickling filter, or biodisc. Because most of the carbonaceous BOD has already been removed, the microorganisms that drive this advanced step are the nitrifying bacteria *Nitrosomonas* and *Nitrobacter*. In nitrification, the ammonia nitrogen is converted to nitrate nitrogen, producing a nitrified effluent. At this point, the nitrogen has not actually been removed, only converted to a form that is not toxic to aquatic life and that does not cause an additional oxygen demand. The nitrification process can be limited by alkalinity (requires 7.3 parts alkalinity to 1.0 part ammonia nitrogen), pH, dissolved oxygen availability, toxicity (ammonia or other toxic materials), and process mean cell residence time (sludge retention time). As a general rule, biological nitrification is more effective and achieves higher levels of removal during the warmer times of the year.

Nitrifier organisms: Bacterial organisms that mediate the biochemical oxidative processes of nitrification.

Nitrobacter: Type of bacteria responsible for the conversion of nitrite to nitrate.

Nitrogenous BOD (NBOD): The biochemical oxygen demand associated with the oxidation of ammonia to nitrite and nitrate.

Nitrosomonas: Type of bacteria responsible for the oxidation of ammonia to the intermediate product nitrite.

Nonbiodegradable: Substances that do not break down easily in the environment.

Non-point source: A source of any water-carried material from a broad area, rather than from discrete points.

Non-point-source contaminant: A substance that pollutes or degrades water; comes from lawn or cropland runoff, the atmosphere, roadways, and other diffuse sources.

Non-point-source water pollution: Water contamination that originates from a broad area (such as leaching of agricultural chemicals from cropland) and enters the water resource diffusely over a large area.

Nonpolar covalently bonded: A molecule composed of atoms that share their electrons equally, resulting in a molecule that does not have polarity.

N/P ratio: The ratio of nitrogen to phosphorus in an aquatic system. The ratio is used as an indicator of the nutrient-limited conditions for algal growth; also used as an indicator for the analysis of trophic levels of receiving waters.

Numerical models: Models that approximate a solution of governing partial differential equations that describe a natural process. The approximation uses a numerical discretization of the space and time components of the system or process.

Nutrient: Any inorganic or organic compound required to sustain plant life.

Organic: Containing carbon, but possibly also containing hydrogen, oxygen, chlorine, nitrogen, and other elements.

- Organic chemical:** A chemical substance of animal or vegetable origin having carbon in its molecular structure.
- Organic detritus:** Any loose organic material in streams—such as leaves, bark, or twigs—removed and transported by mechanical means, such as disintegration or abrasion.
- Organic loading:** The number of pounds of BOD added to a treatment unit per day.
- Organic matter:** The organic fraction that includes plant and animal residue at various stages of decomposition, cells and tissues of soil organism, and substances synthesized by the soil population. Commonly determined as the amount of organic material contained in a soil or water sample.
- Organic nitrogen:** Organic form of nitrogen bound to organic matter.
- Organic soil:** Soil that contains more than 20% organic matter in the upper 16 inches.
- Organochlorine compound:** Synthetic organic compounds containing chlorine. As generally used, the term refers to compounds containing mostly or exclusively carbon, hydrogen, and chlorine.
- Outfall:** Point where wastewater or stormwater flows from a conduit, stream, or drainage ditch into natural waters.
- Outwash:** Soil material washed down a hillside by rainwater and deposited upon more gently sloping land.
- Overland flow:** The flow of rainwater or snowbelt over the land surface toward stream channels.
- Oxidation:** Occurs when a substance either gains oxygen or loses hydrogen or electrons in a chemical reaction; one of the chemical treatment methods.
- Oxidizer:** A substance that oxidizes another substance.
- Oxygen available:** The oxygen available for aerobic stabilization of organic matter; includes dissolved oxygen and oxygen available in nitrites or nitrates, peroxides, ozone, and certain other forms of oxygen.
- Oxygen demand:** Measure of the dissolved oxygen used by a system (microorganisms) or chemical compounds in the oxidation of organic matter.
- Oxygen depletion:** Deficit of dissolved oxygen in a natural waters system due to oxidation of the natural and anthropogenic organic matter.
- Oxygen sag:** Description of characteristic spatial trend of the concentration of dissolved oxygen in a stream or river downstream of a high loading rate of oxygen-demanding materials from tributaries, municipal or industrial wastewater dischargers, or urban stormwater and combined sewer overflow systems.
- Oxygen saturation:** The maximum amount of oxygen gas that can be dissolved in natural waters by transfer of oxygen from the atmosphere across the air/water interface. The concentration of oxygen saturation is greatly influenced by water temperature, salinity or chloride concentration, and elevation above the mean sea level, in addition to other water characteristics.
- Parameters:** Constituents measured in water quality monitoring programs. Examples include dissolved oxygen, BOD₅, total dissolved solids, and water temperature.

- Parts per million (PPM):** Number of weight or volume units of a constituent present in each 1 million units of the solution or mixture. Formerly used to express the results of most water and wastewater analyses, PPM is being replaced by milligrams per liter (mg/L). For drinking water analyses, concentration in parts per million and milligrams per liter are equivalent. A single PPM can be compared to a shot glass filled from water of a standard swimming pool.
- Parts per thousand (PPT):** Measure of concentration; 1 part solute to 1000 parts water (by weight).
- Pathogens:** Microorganisms that can cause disease.
- Per-capita use:** The quantity of water used per person per day averaged over a time interval of 1 day; expressed as gallons per capacity per day (gpcd).
- Perched groundwater:** Unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone.
- Percolation:** The movement, under hydrostatic pressure, of water through interstices of a rock or soil (except the movement through large openings such as caves).
- Perennial stream:** A stream that normally has water in its channel at all times.
- Periphyton:** Microorganisms that coat rocks, plants, and other surfaces on lake bottoms.
- Permeability:** The capacity of a rock for transmitting a fluid; a measure of the relative ease with which a porous medium can transmit a liquid.
- pH:** A measure of the acidity (less than 7) or alkalinity (greater than 7) of a solution; a pH of 7 is considered neutral.
- Phosphorus:** A nutrient essential for growth that can play a key role in stimulating aquatic growth in lakes and streams.
- Photosynthesis:** The synthesis of compounds with the aid of light.
- Physical treatment:** Any process that does not produce a new substance (e.g., screening, adsorption, aeration, sedimentation, filtration).
- Phytoplankton:** A group of generally unicellular microscopic plants characterized by passive drifting within the water column.
- Plankton:** Group of generally microscopic plants and animals passively floating, drifting, or swimming weakly. Plankton include the phytoplankton (plants) and zooplankton (animals).
- Point source:** Originating at any discrete source.
- Polar covalent bond:** The shared pair of electrons between two atoms are not equally held; thus, one of the atoms becomes slightly positively charged and the other atom becomes slightly negatively charged.
- Polar covalent molecule:** One or more polar covalent bonds result in a molecule that is polar covalent. Polar covalent molecules exhibit partial positive and negative poles, causing them to behave like tiny magnets. Water is the most common polar covalent substance.
- Pollutant:** Any substance introduced into the environment that adversely affects the usefulness of the resource.
- Pollution:** The presence of matter or energy whose nature, location, or quantity produces undesired environmental effects. Under the Clean Water Act, for example, the term is defined as a manmade or human-induced alteration of the physical, biological, and radiological integrity of water.

- Polychlorinated biphenyls (PCBs):** A mixture of chlorinated derivatives of biphenyl marketed under the tradename Aroclor with a number designating the chlorine content (such as Aroclor 1260). PCBs were used in transformers and capacitors for insulating purposes and in gas pipeline systems as a lubricant. Further sale or new use was banned by law in 1979.
- Polycyclic aromatic hydrocarbon (PAH):** A class of organic compounds with a fused-ring aromatic structure. PAHs result from incomplete combustion of organic carbon (including wood), municipal solid waste, and fossil fuels, as well as from natural or anthropogenic introduction of uncombusted coal and oil. PAHs include benzo(a)pyrene, fluoranthene, and pyrene.
- Population:** A collection of individuals of one species or mixed species making up the residents of a prescribed area.
- Population equivalent:** The calculated population that would normally contribute the same amount of biochemical oxygen demand as the wastewater. A common base is 0.2 lb (0.09 kg) of 5-day BOD per capita per day.
- Porosity:** The ratio of the volume of voids in a rock or soil to the total volume.
- Potable water:** Water that is safe and palatable for human consumption.
- Precipitation:** Any or all forms of water particles that fall from the atmosphere, such as rain, snow, hail, and sleet; the act or process of producing a solid phase within a liquid medium.
- Pretreatment:** Any physical, chemical, or mechanical process used before the main water treatment processes. It can include screening, presedimentation, and chemical addition.
- Primary drinking water standards:** Regulations on drinking water quality (under the Safe Drinking Water Act) considered essential for preservation of public health.
- Primary productivity:** A measure of the rate at which new organic matter is formed and accumulated through the photosynthesis and chemosynthesis activity of producer organisms (chiefly, green plants). The rate of primary production is estimated by measuring the amount of oxygen released (oxygen method) or the amount of carbon assimilated by the plant (carbon method).
- Primary treatment:** The first step of treatment at a municipal wastewater treatment plant. It typically involves screening and sedimentation to remove materials that float or settle. The process typically removes about 25 to 35% of solids and related organic matter (BOD_5).
- Public-supply withdrawals:** Water withdrawn by public and private water suppliers for use within a general community. Water is used for a variety of purposes (e.g., domestic, commercial, industrial).
- Public water system:** Defined by the Safe Drinking Water Act as any system, publicly or privately owned, that serves at least 15 service connections 60 days out of the year or serves an average of 25 people at least 60 days out of the year.
- Publicly owned treatment works (POTW):** A wastewater treatment works owned by a state, local government unit, or Indian tribe, usually designed to treat domestic wastewaters.
- Rain shadow:** A dry region on the lee side of a topographic obstacle, usually a mountain range, where rainfall is noticeably less than on the windward side.

Range: Statistical measure expressing the difference between the minimum and maximum values recorded for a given constituent in time and space.

Raw sewage: Untreated municipal sewage.

Reach (of a river): A continuous part of a stream between two specified points.

Reaeration: The net flux of oxygen transferred from the atmosphere to a body of water with a free surface; the replenishment of oxygen in water from which oxygen has been removed.

Reaeration rate coefficient: Coefficient describing the rate of transformation of a substance in an environmental medium characterized by a set of physical, chemical, and biological conditions such as temperature and dissolved oxygen level.

Receiving waters: A river, lake, ocean, stream, or other water source into which wastewater or treated effluent is discharged.

Recharge: The process by which water is added to a zone of saturation, usually by percolation from the soil surface.

Recharge area (groundwater): An area within which water infiltrates the ground and reaches the zone of saturation.

Reference dose (RfD): An estimate of the amount of a chemical that a person can be exposed to on a daily basis that is not anticipated to cause adverse systemic health effects over the person's lifetime.

Removal efficiency: A measure of how much of a pollutant is removed from raw sewage prior to discharge into receiving water after completion of wastewater treatment processes; removal percent is expressed as $[(\text{influent} - \text{effluent})/(\text{influent})] \times 100$.

Representative sample: A sample containing all the constituents present in the water from which it was taken.

Respiration: Biochemical process by means of which cellular fuels are oxidized with the aid of oxygen to permit the release of the energy required to sustain life; during respiration, oxygen is consumed and carbon dioxide is release.

Return flow: Irrigation water that is not consumed by evapotranspiration and that returns to its source or another body of water.

Reverse osmosis (RO): Solutions of differing ion concentration are separated by a semipermeable membrane. Typically, water flows from the chamber with the lesser ion concentration into the chamber with the greater ion concentration, resulting in hydrostatic or osmotic pressure. In RO, enough external pressure is applied to overcome this hydrostatic pressure, thus reversing the flow of water. This results in the water on the other side of the membrane becoming depleted in ions and demineralized.

Riffle: A shallow part of the stream where water flows swiftly over completely or partially submerged obstructions to produce surface agitation.

Riparian: Pertaining to or located on the bank of a body of water, especially a stream.

Riparian rights: A concept of water law under which authorization to use water in a stream is based on ownership of the land adjacent to the stream.

Rotating biological contactors (RBCs): A wastewater treatment process consisting of a series of closely spaced rotating circular disks of polystyrene or polyvinyl chloride. Attached biological growth is promoted on the surface of the disks. The rotation of the disks allows contact with the wastewater and the atmosphere to enhance oxygenation.

Runoff: Precipitation or snowmelt that appears in streams or surface water bodies.

Rural withdrawals: Water used in suburban or farm areas for domestic and livestock needs. The water generally is self-supplied and includes domestic use, drinking water for livestock, and other uses such as dairy sanitation, evaporation from stock-watering ponds, and cleaning and waste disposal.

Safe Drinking Water Act (SDWA): A federal law passed in 1974 with the goal of establishing federal standards for drinking water quality, protecting underground sources of water, and setting up a system of state and federal cooperation to ensure compliance with the law.

Saline water: Water that is considered unsuitable for human consumption or for irrigation because of its high content of dissolved solids; generally expressed as milligrams per liter (mg/L) of dissolved solids (e.g., seawater is generally considered to contain more than 35,000 mg/L of dissolved solids). A general salinity scale is provided below:

Slightly saline	1000 to 3000 mg/L dissolved solids
Moderately saline	3000 to 10,000 mg/L dissolved solids
Very saline	10,000 to 35,000 mg/L dissolved solids
Brine	More than 35,000 mg/L dissolved solids

Saturated zone: A subsurface zone in which all the interstices or voids are filled with water under pressure greater than that of the atmosphere.

SAV: Submersed or submerged aquatic vegetation; rooted aquatic plants that grow in shallow clear water.

Screening: A pretreatment method that uses coarse screens to remove large debris from the water to prevent clogging of pipes or channels to the treatment plant.

Secchi depth: A measure of light penetration into the water column; light penetration is influenced by turbidity.

Secondary drinking water standards: Regulations developed under the Safe Drinking Water Act that established maximum levels of substances affecting the aesthetic characteristics (taste, color, or odor) of drinking water.

Secondary maximum contaminant level (SMCL): The maximum level of a contaminant or undesirable constituent in public water systems that, in the judgment of the USEPA, is required to protect the public welfare. SMCLs are secondary (nonenforceable) drinking water regulations established by the USEPA for contaminants that may adversely affect the odor or appearance of water.

Secondary treatment: The second step of treatment at a municipal wastewater treatment plant. This step uses growing numbers of microorganisms to digest organic matter and reduce the amount of organic waste. Water leaving this process is chlorinated to destroy any disease-causing microorganisms before its release.

Sediment: Particulate organic and inorganic matter that accumulates in a loose, unconsolidated form on the bottom of natural waters.

Sediment oxygen demand (SOD): The solids discharged to the receiving water are partly organics, and upon settling to the bottom they decompose anaerobically as well as aerobically, depending on conditions. SOD is a measure of the amount of oxygen consumed in the sediment bed during aerobic decomposition of detrital organic carbon deposited on the bottom of a water body; it represents another dissolved oxygen loss/sink for the water body.

Sedimentation: A physical treatment method that involves reducing the velocity of water in basins so that the suspended material can settle out by gravity.

Seep: A small area where water percolates slowly to the land surface.

Seiche: A sudden oscillation of the water in a moderate-size body of water, caused by wind.

Settleable solids: Solids that will settle out when a sample of sewage is allowed to stand quietly for a 1-hour period.

Short-circuiting: The hydraulic conditions in a tank, chamber, or basin where the time of passage is less than that of the normal flow-through period.

Significance level: A statistical measure of the certainty that can be associated with the results of a statistical analysis.

Sinuosity: The ratio of channel length between two points on the channel to the straight-line distance between the same two points; a measure of meandering.

Sludge banks: The accumulation of solids, including silt, mineral, organic, and cell mass material, produced in an aquatic system.

Soil horizon: A layer of soil that is distinguishable from adjacent layers by characteristic physical and chemical properties.

Soil moisture: Water occurring in the pore spaces between the soil particles in the unsaturated zone from which water is discharged by the transpiration of plants or by evaporation from the soil.

Solution: Formed when a solid, gas, or another liquid in contact with a liquid becomes dispersed homogeneously throughout the liquid. The substance, called a *solute*, is said to dissolve. The liquid is called the *solvent*.

Solvated: Occurs when either a positive or a negative ion becomes completely surrounded by polar solvent molecules.

Sorb: To take up and hold either by absorption or adsorption.

Sorption: General term for the interaction (binding or association) of a solute ion or molecule with a solid.

Specific yield: The ratio of the volume of water that will drain under the influence of gravity to the volume of saturated rock.

Spring: Place where a concentrated discharge of groundwater flows at the ground surface.

Stabilization: The process of reducing a material using biological and chemical means to a form that does not readily decompose.

Stabilization ponds: Large earthen basins that are used for the treatment of wastewater by natural processes involving the use of both algae and bacteria.

Standard Industrial Classification (SIC) codes: Four-digit codes established by the Office of Management and Budget (OMB) to classify commercial and manufacturing establishments by the principal type of activity; for example, 4952 represents a municipal wastewater treatment plant.

Standard methods: Methods of analysis prescribed by joint action of the American Public Health Association, American Water Works Association, and Water Pollution Control Federation.

Station (monitoring): Specific location in a water body chosen to collect water samples for the measurement of water quality constituents. Stations are identified by an alphanumeric code identifying the agency source responsible for the collection of the data and a unique identifier code designating the location. Station measurements can be recorded from discrete grab samples or continuous automated data acquisition systems. Station locations are typically sampled by state, federal, or local agencies at periodic intervals (e.g., weekly, monthly, annual) as part of a routine water quality monitoring program to track trends. Station locations can also be sampled only for a period of time needed to collect data for an intensive survey or a special monitoring program.

Stoichiometric ratio: Mass-balance-based ratio used for nutrients, organic carbon, dry weight, and algae (e.g., nitrogen-to-carbon ratio).

STORET: USEPA national water quality database for storage and retrieval; a main-frame water quality database that includes millions of records of physical, chemical, and biological data measured in water bodies throughout the United States.

Storm runoff: Rainfall that does not evaporate or infiltrate into the ground because of impervious land surfaces or a soil infiltration rate lower than rainfall intensity, but instead flows onto adjacent land or waterbodies or is routed into a drain or sewer system.

Stream order: A ranking of the relative size of streams and rivers within a watershed based on the network of tributaries. Figure G.1 indicates the Strahler stream ordering process. Numbering begins at the top of a catchment

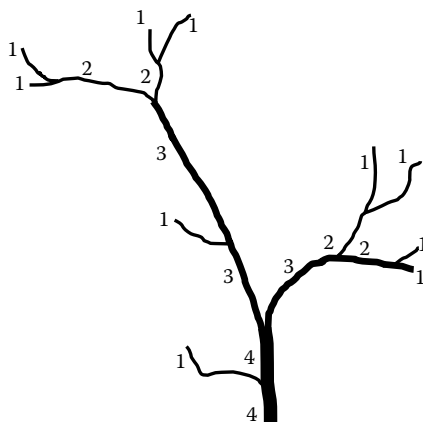


FIGURE G.1 Strahler stream order.

with headwater (“new”) flow paths being assigned the number 1. Where two flow paths of order 1 join, the section downstream of the junction is referred to as a second-order stream. Where two second-order streams join, the waterway downstream of the junction is referred to as a third-order stream, and so on. Where a lower order stream (e.g., first order) joins a higher order stream (e.g., third order), the area downstream of the junction will retain the higher number (i.e., it will remain a third-order stream). Generally, third-order streams and above are likely to display valuable fish habitat and hence could support viable fish populations. As a result, fish passage barriers located on third-order and above waterways should be considered for remediation.

Streamflow: Discharge that occurs in a natural channel. Although the term “discharge” can be applied to the flow of a canal, the word “streamflow” uniquely describes the discharge in a surface stream course and is more general than “runoff,” as streamflow may be applied to discharge whether or not it is affected by diversion or regulation.

Supersaturation: The situation in which water holds more oxygen at a specified temperature than normally required for saturation.

Surface runoff: Runoff that travels over the land surface to the nearest stream channel.

Surface tension: The attractive forces exerted by molecules below the surface on those at the surface, resulting in them crowding together and forming a higher density.

Surface water: All water naturally open to the atmosphere, and all springs, wells, or other collectors that are directly influenced by surface water.

Surface Water Treatment Rule (SWTR): A federal regulation established by the USEPA under the Safe Drinking Water Act that imposes specific monitoring and treatment requirements on all public drinking water systems that draw water from a surface water source.

Suspended sediment: Sediment that is transported in suspension by a stream.

Suspended solids: Different from suspended sediment only in the way that the sample is collected and analyzed.

Synthetic organic chemicals (SOCs): Manufactured chemicals that are not as volatile as volatile organic chemicals. Included are herbicides, pesticides, and chemicals widely used in industries.

10th percentile: A low-end statistic based on ranking a dataset from the minimum to the maximum value. The 10th percentile defines the value for which 10% of the ranked dataset is less than the statistic and 90% of the dataset is greater than the statistic. Used to define “worst-case” conditions for the evaluation of before and after trends of dissolved oxygen.

Tertiary treatment: Wastewater treatment processes designed to remove or alter the forms of nitrogen or phosphorus compounds contained in domestic sewage.

Total coliform bacteria: A particular group of bacteria used as indicators of possible sewage pollution.

Total head: The height above a datum plane of a column of water. In a groundwater system, it is composed of elevation head and pressure head.

- Total Kjeldahl nitrogen (TKN):** The sum total of organic and ammonia nitrogen in a sample, determined by the Kjeldahl method.
- Total maximum daily load (TMDL):** The sum of the individual wasteload allocations and load allocations. A margin of safety is included with the two types of allocations so that any additional loading, regardless of sources, would not produce a violation of water quality standards.
- Total solids:** Refers to the solids contained in dissolved and suspended form in water; determined by weighing after drying at 103°C.
- Total suspended solids (TSS):** Solids present in wastewater.
- Toxic substances:** Those chemical substances, such as pesticides, plastics, heavy metals, detergent, solvent, or any other materials that are poisonous, carcinogenic, or otherwise directly harmful to human health, biota, and the environment.
- Transpiration:** The process by which water passes through living organisms, primarily plants, into the atmosphere.
- Transport of pollutants (in water):** Involves advection, resulting from the flow of water, and diffusion (transport) due to turbulence mixing in the water.
- Tributary:** A lower order stream compared to a receiving water body. The designation of “tributary to” indicates the largest stream into which the reported stream or tributary flows.
- Trickling filter:** A wastewater treatment process consisting of a bed of highly permeable medium (e.g., gravel or stones) to which microorganism are attached and through which wastewater is percolated or trickled over the biofilm that forms on the media.
- Trihalomethanes (THMs):** A group of compounds formed when natural organic compounds from decaying vegetation and soil (such as humic and fulvic acids) react with chlorine.
- Turbidity:** A measure of the cloudiness of water caused by the presence of suspended matter, which shelters harmful microorganisms and reduces the effectiveness of disinfecting compounds.
- Ultimate biochemical oxygen demand (UBOD, BODU):** Long-term oxygen demand required to completely stabilize organic carbon and ammonia in wastewater or natural waters; defined as the sum of ultimate carbonaceous BOD and nitrogenous BOD.
- Unconfined aquifer:** An aquifer whose upper surface is a water table free to fluctuate under atmospheric pressure.
- Unsaturated zone:** A subsurface zone above the water table in which the pore spaces may contain a combination of air and water.
- Urban drainage:** Water derived from surface runoff or shallow groundwater discharge from urban land use areas.
- Vehicle of disease transmission:** Any nonliving object or substance contaminated with pathogens.
- Vernal pool:** A small lake or pond that is filled with water for only a short time during the spring.
- Volatile solids:** The quantity of solids in water that represent a loss in weight upon ignition at 550°C.

- Wastewater:** The spent or used water from individual homes, a community, a farm, or an industry that contains dissolved or suspended matter.
- Wastewater treatment:** Chemical, biological, and mechanical processes applied to an industrial or municipal discharge or to any other sources of contaminated water in order to remove, reduce, or neutralize contaminants prior to discharge to receiving water.
- Water budget:** An accounting of the inflow to, outflow from, and storage changes of water in a hydrologic unit.
- Water column:** An imaginary column extending through a water body from its floor to its surface.
- Water demand:** Water requirements for a particular purpose, such as irrigation, power, municipal supply, plant transpiration, or storage.
- Water pollution:** Any condition of a water body that reflects unacceptable water quality or ecological conditions. Water pollution is usually the result of discharges of waste material from human activities into a water body.
- Water quality:** Numerical description of the biological, chemical, and physical conditions of a water body. It is a measure of a water body to support beneficial uses.
- Water softening:** A chemical treatment method that uses either chemicals to precipitate or a zeolite to remove the metal ions (typically Ca^{2+} , Mg^{2+} , Fe^{3+}) responsible for hard water.
- Water table:** The top water surface of an unconfined aquifer at atmospheric pressure.
- Waterborne disease:** Water is a potential vehicle of disease transmission, and waterborne disease is possibly one of the most preventable types of communicable illness. The application of basic sanitary principles and technology has virtually eliminated serious outbreaks of waterborne diseases in developed countries. The most prevalent waterborne diseases include typhoid fever, dysentery, cholera, infectious hepatitis, and gastroenteritis.
- Watershed:** Land area that drains into a river, river system, or other body of water.
- Wellhead protection:** Protection of the surface and subsurface areas surrounding a water well or well field supplying a public water system from contamination by human activity.
- Yield:** The mass of material or constituent transported by a river in a specified period of time divided by the drainage area of the river basin.
- Zooplankton:** Very small animals (protozoans, crustaceans, fish embryos, insect larvae) that live in a water body and are moved passively by water currents and wave action.

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Wastewater Stabilization Ponds

Ponds (lagoons) have been used for centuries with great success in the treatment of wastewater. Ponds created for treatment, known as stabilization ponds, model the physical and biochemical interactions that occur in natural ponds. Easy to build and manage, stabilization ponds can accommodate large fluctuations in flow, and provide results that are comparable to conventional systems at a much lower cost. *Wastewater Stabilization Ponds* examines the use of this natural and highly effective process. The text is centered on wastewater pond management processes and operation procedures that provide passive treatment with a minimum of energy-driven mechanical elements.

The book highlights the environmental principles, practices, engineering, and mathematics involved in the design and operation of conventional wastewater stabilization ponds. It also explores the major processes, procedures, and design methods relevant to wastewater treatment ponds. This includes the basic processes, in-pond design evolution and enhancements, oxygen addition, and modifications that require energy, nutrient removal, as well as effluent total suspended solids removal. Emphasizing the design, construction, and operation of wastewater ponds, the book serves as a valuable resource for anyone seeking information on pond construction and operation, knowledge of pond operation, and assistance in certification exam preparation and study.

- Presents a design of wastewater stabilization ponds
- Includes a complete description of pond process elements
- Provides descriptions of pond insect macroinvertebrates
- Incorporates pond morphometry calculations
- Contains extensive pond-related math problems

Sustainability and energy conservation are underlying themes throughout the text and the authors offer valuable information on potential renewable energy sources.