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TREATMENT LAGOONS FOR ANIMAL AGRICULTURE[1]

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SUMMARY

The term "lagoon" is often misused. Farmers, the press, and the public tend to call all earthen manure storages basins lagoons. The term "lagoon," however, has a specific meaning. ASAE Standards define a lagoon as "a waste treatment impoundment…(in which manure) is mixed with sufficient water to provide a high degree of dilution…for the primary purpose…(of reducing) pollution potential through biological activity. Treatment lagoons are not drawn below their treatment volume…except for maintenance."

Many of the problems associated liquid manure handling systems: liner seepage, accidental overflows, catastrophic embankment failure, pathogen release, odor emissions, and closure of earthen basins are not unique to lagoon-based systems. These problems are shared by all liquid systems. Other white papers in this volume touch upon these issues. The emphasis of this paper is the biological treatment potential of lagoons.

Lagoons rely on physical, chemical, and biological processes to degrade manure. Biological processes play the greatest role in degradation. Growth and maintenance of biological communities depend on temperature, food, the absence of toxic elements, and the ability of organisms to remain in the lagoon long enough to reproduce.

Microbiological communities are vertically segregated in lagoons. Each layer performs a separate function in the overall treatment process. Photosynthetic organisms play a major role in the degradation of sulfur- and nitrogen-containing compounds, as well as odoriferous elements; therefore the presence of the proper wavelengths of light to perform photosynthesis is also important in lagoon biology.

Lagoons function best when operated as flow-through systems with a mechanism to periodically remove effluent. The most common method of effluent removal is to recycle plant nutrients through irrigation to crops. Local patterns of rainfall and evaporation (and the amount of rain produced by isolated storm events) determine whether a lagoon has a net surplus of effluent or whether water must be added to the system to maintain material flow through the lagoon.

Two challenges must be addressed if lagoons are to remain a viable treatment alternative for animal agriculture:

1. Inefficient recovery of plant nutrients, and
2. Odor and ammonia emissions.

Up to 80% of all nitrogen entering lagoons cannot be accounted for in lagoon effluent, and a great portion of manure phosphorus entering lagoons is retained in sludge. Plant nutrients are less concentrated in lagoon effluent than in other manure treatment products, although lagoon effluent has a better balance of nitrogen to soluble phosphorus than most sources of manure nutrients. Lagoon effluent should be used in crop production on a nitrogen basis, irrigating effluent in multiple

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applications throughout the growing season. Managing effluent in this manner requires expensive, permanent irrigation equipment to apply what is essentially low quality fertilizer. Nitrogen application is inherently out of sync with phosphorus since the majority of manure phosphorus is only recovered when solids are removed at the end of the sludge storage cycle, which may last as long as 10 to 20 years.

Large chemical compounds are transformed into smaller, more volatile compounds through biological degradation. These small compounds may be less odorous than those found in raw manure, but their volatility makes them more likely to be emitted into the atmosphere. Ammonia gas is produced during anaerobic degradation of proteins and urea. A portion of the ammonia created in lagoons is undoubtedly lost through atmospheric emission. However, recent studies suggest that much of the atmospheric release of nitrogen may be in the form of harmless N_2 gas.

Lagoons located in temperate climates undergo annual cycles of storage, heating, and organic matter accumulation. Cool season organic matter accumulation is most pronounced in extreme latitudes. The heating and organic matter accumulation cycles are problematic in that there is a tendency for lagoon layers to become unstable in the spring and fall, increasing the likelihood of odor emissions during these periods.

The mass of atmospheric emissions increases with lagoon size, and many of the problems of liquid manure handling—liner seepage, the consequences of catastrophic failures, wave erosion—are exacerbated by lagoon size. Current anaerobic lagoon design standards rely on volumetric organic loading rate to size the treatment volume. This means that lagoon size is directly proportional to farm size. A second consequence of relying on volumetric loading rate as the sole design parameter is that lagoon geometry cannot be changed without altering other potentially important design parameters such as depth and surface area to volume ratio.

This paper does not specify a maximum size for lagoons, nor does it advocate abandoning volumetric loading rate as a design parameter. Pretreatment to reduce the mass of organic matter entering lagoons is suggested as a method to limit lagoon size on larger farms. Improvements in lagoon performance will be realized when specific biological communities, prescribed to perform specific treatment steps, are engineered to be present in individual lagoon cells or layers. Design refinements are needed to reach this point. Research should focus on filling the following information gaps:

1. Achieve a greater understanding of the fundamental biological processes involved in manure degradation.
2. Achieve a greater understanding of the chemical transformations involved in lagoon treatment.
3. Achieve a greater understanding of the physical and climatic factors that lead to cyclic environmental conditions experienced by lagoon microorganisms in temperate climates.
4. Develop diagnostic tools capable of monitoring biological communities in natural environments.
5. Develop design parameters to promote specific, robust biological communities in lagoons, given a set of environmental conditions and influent characteristics.

Educational materials must be produced to train operators to maintain lagoons. These materials should be sensitive to the operators' need to work within the limitations of an agricultural production system. The curriculum should include:

1. Basic treatment biology;
2. The cyclic nature of lagoon operation;
3. Liquid balance to maintain proper lagoon operating levels;
4. Operating within an actual water year, not an average year;
5. Efficient nutrient use; and
6. Maintaining structural integrity.

USE OF LAGOONS IN ANIMAL AGRICULTURE

In almost all cases, lagoons serve as storage and treatment components of manure handling systems that recycle manure nutrients through crop production. A simplified lagoon-based handling system is shown in Figure 1. Although land application is not an essential element of lagoon treatment, liquids must past through the lagoon. Lagoons are biological processors—similar to an animal's stomach and intestines. If material does not move through the system, the lagoon will not function properly.

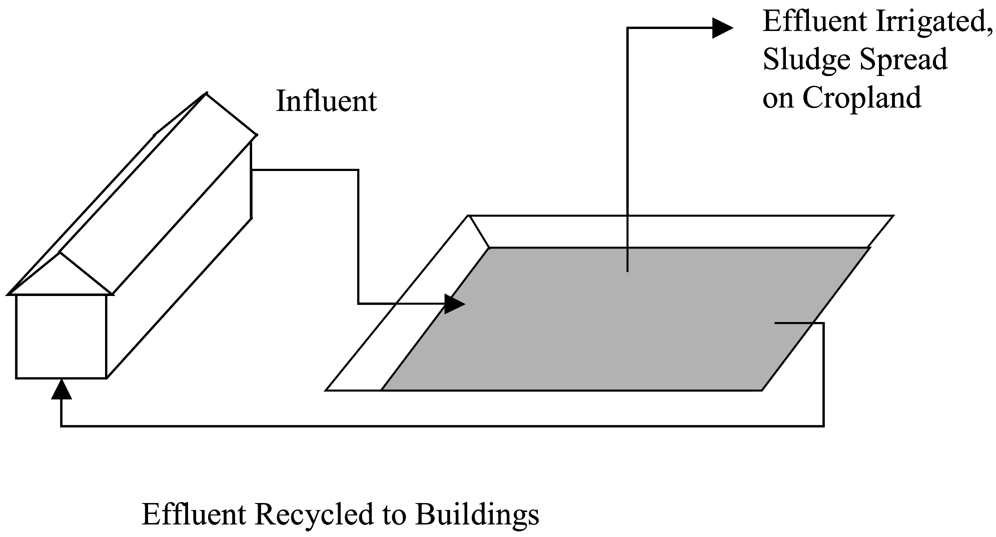


Figure 1. Simplified lagoon-based manure handling system.

The lagoon provides storage for both treated liquids (effluent) and solids (sludge). Effluent storage is provided to maximize recycling of nutrients. With proper storage (plus adequate planning and irrigation equipment) effluent may be applied precisely at times plants are using nutrients. Manure solids are digested into sludge. Sludge storage is provided within the lagoon so that the growth of sludge does not decrease the liquid volume of the lagoon beyond a minimum value. Under current practices, sludge is removed at a frequency of 5 to 20 years and applied to the soil. Soluble plant nutrients—nitrogen and potassium—are found primarily in lagoon effluent; whereas less soluble nutrients—phosphorus, calcium—are associated with sludge (Fulhage, 1980). The difference between nitrogen and phosphorus solubility in lagoons means that the nutrients are handled in fundamentally different ways. Nitrogen is recycled on an annual basis. A longer time frame must be considered to completely recycle phosphorus in crop production.

Treatment is defined in agricultural operations as any process that alters the volume or character of raw materials to improve handling, reuse, appearance, odor, or safety. To this end, lagoons perform a number of functions within the manure handling system shown in Figure 1. They separate solids from liquids so that liquid handling pumps and equipment may be used to irrigate effluent. Nutrients and organic matter contained in effluent are made soluble for efficient crop and soil uptake. Effluent is treated to a sufficient quality to be recycled back into the buildings. Lagoons minimize nuisance conditions, atmospheric emissions, and odors. Finally, lagoons reduce pathogens in effluent and sludge.

Lagoons are used primarily in systems that remove waste from buildings in a liquid form. Lagoons are frequently found on swine farms, because swine waste is easily transported as a liquid. Dairy farms also use lagoons due to large amounts of liquids needed to clean housing and milking facilities. Although many older laying hen farms in the southeastern United States still operate lagoons, lagoons are used less frequently in poultry production due to poor liquid transport of waste. Lagoons are rarely used with open beef feedlots, because large runoff volumes cause the storage function to overwhelm treatment.

LAGOON NOMENCLATURE

Lagoons are classified as single-cell (sometimes called single-stage) or multi-cell (multi-stage) based on the number of earthen basins used in the total treatment system. All treatment and storage functions take place within a single earthen basin with a single-cell lagoon (Figure 2). Effluent is generally removed from the upper 1 or 2 ft (0.3 to 0.6 m) of the liquid surface of a single-cell lagoon for recycling to buildings and irrigation. Multi-cell lagoons have treatment and storage functions divided between two or more earthen basins. Figure 3 shows the layout of a two-cell lagoon.

As will be shown in the next section, manure degradation in lagoons is heavily dependent on the biological communities present in the treatment volume. *Anaerobic* treatment takes place in the absence of oxygen. Dissolved oxygen (DO) is always measurable in *aerobic* systems. *Facultative*

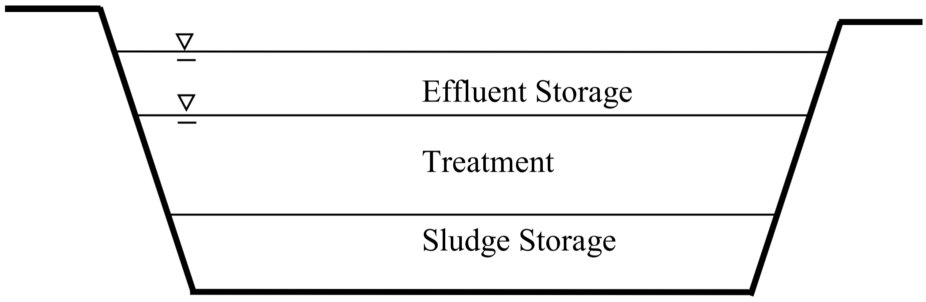


Figure 2. Single-cell lagoon schematic.

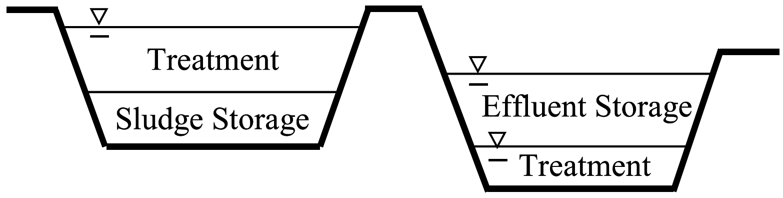


Figure 3. Two-cell lagoon schematic.

systems can function with or without the presence of DO. The definition of facultative systems is somewhat complicated. Facultative lagoons may have DO present in only a portion of the treatment volume, or DO may be present temporarily throughout the treatment volume, or DO may be used by biological communities at concentrations too small to be measured.

Lagoons may also be defined as covered or uncovered depending on whether or not their liquid surface is open to the atmosphere. Covers impermeable to gases (plastic, rubber, etc.) are used to ensure that an anaerobic environment exists in the lagoon. Thick gas- and liquid-permeable covers (straw, polystyrene beads sandwiched between geotextile fabric) may be used to ensure an aerobic environment exists within the cover itself. Dairy lagoons that naturally form thick permeable crusts may also be thought of as covered anaerobic lagoons.

Putting all the nomenclature together: a three-cell lagoon may have a covered, anaerobic cell as its first stage, an open, facultative cell as its second stage, and an open, aerobic cell as its third stage.

AGRICULTURAL LAGOON DESIGN

Three entities have lead in the development of lagoon design in North America: the Midwest Plan Service (MWPS), the American Society of Agricultural and Biological Engineers (ASABE; until mid-2005 called ASAE), and the United States Department of Agriculture Natural Resources Conservation Service (USDA-NRCS). MWPS standards have been eclipsed by ASAE (ASABE) and USDA-NRCS in recent years, mainly due to the influence of the rational design standard for agricultural lagoons proposed by Barth (1985). Agricultural lagoon design falls into five categories: uncovered anaerobic/facultative lagoons, covered anaerobic lagoons, naturally aerated lagoons, mechanically aerated lagoons, and hybrid anaerobic/aerobic lagoons.

Uncovered Anaerobic/Facultative Lagoons

The uncovered anaerobic/facultative lagoon is the most common type of treatment lagoon used in animal agriculture. Originally, uncovered lagoons were designed based solely on anaerobic treatment, but in recent years, photosynthetic and facultative microorganisms have come to play a larger role in treatment design due to their ability to reduce nuisance conditions. It is more accurate to refer to these lagoons as uncovered anaerobic/facultative lagoons. Single-cell, uncovered anaerobic/facultative lagoons are relatively deep bodies of liquid. This depth provides adequate sludge storage and ensures that treatment takes place in layered biological communities. As will be discussed in the Annual and Diurnal Cycles section of this paper, single-cell, uncovered anaerobic/ facultative lagoons are not complete mixed reactors. They can be viewed as a two-layered system with a completely mixed zone resting atop an unmixed zone.

The Rational Design Standard for Anaerobic Lagoons

The title "Rational Design Standard" is somewhat misleading in that it is not a standard prepared by a governing body. It is a design method proposed at ASAE's Fifth International Symposium on

Agricultural Wastes (Barth, 1985). The methodology proposed in the paper has had a profound impact on the development of anaerobic lagoon design since 1985. The rational design standard was the first significant attempt to design agricultural lagoons by dividing the total lagoon into component parts as shown in Figures 2 and 3.

Minimum treatment volume is determined by dividing the mass of volatile solids (VS) added to the lagoon each day by a volumetric loading factor. This factor is based on observations of lagoons approaching failure due to sludge accumulation in South Carolina (Barth and Kroes, 1985). The observed rates apply only to the locations at which they were measured. Determination of loading rates for other locations is based on earlier work of Smith and Franco (1985) using the Van't Hoff-Arrhenius equation. The Van't Hoff-Arrhenius equation allows determination of a daily biological activity rate (KT) based on temperature. Barth determined annual biological activity (KTA) for 102 locations in the continental United States by adding together the daily KT on days with average temperature above 5°C. Five degrees C is assumed to be the temperature at which acid-forming bacteria became active. A lagoon activity ratio (K) was then determined at all 102 locations by dividing KTA by 365. Minimum treatment volume is, therefore, determined by consulting a map of Iso-K lines (Figure 4) drawn for the continental United States. Minimum treatment volume can be calculated for any location in the continental U.S. using this map and a base volumetric organic loading rate. Barth determined base rates to be 6.2 lbs VS/1000ft^3-day (100 kg/1000 m^3-day) for swine and poultry, and 10.5 lbs VS/1000 ft^3-day (170 kg/1000 m^3-day) for dairy.

Barth also recommended volumetric loading rates for odor control based on previous studies on swine (Humenik et al., 1980) and poultry lagoons (Barth and Hegg, 1984). Volumetric organic loading rates for odor control were determined to be 3.8 lbs VS/1000ft^3-day (61 kg/1000 m^3-day) for swine and 2.55 lbs VS/1000ft^3-day (41 kg/1000 m^3-day) for poultry. These rates can also be adjusted for any location by multiplying the rate by the K values shown in Figure 4. It is important to note that odor control rates apply to daily influent organic matter divided by the entire volume of the lagoon – minimum treatment and sludge storage volumes.

ASAE Standard for Anaerobic Lagoons

ANSI/ASAE Standard EP403.3 JUL99 Design of Anaerobic Lagoons for Animal Waste Management (ASAE Standards, 1999) is a voluntary design standard promulgated by ASAE. Recommended maximum volumetric organic loading rates are given for general climatic regions of the U.S. based on average monthly temperatures and the expected amount of biological activity (Figure 5). Recommended values range from 3 to 6 lb VS/1000ft^3-day (48 to 96 kg/1000 m^3-day) in the

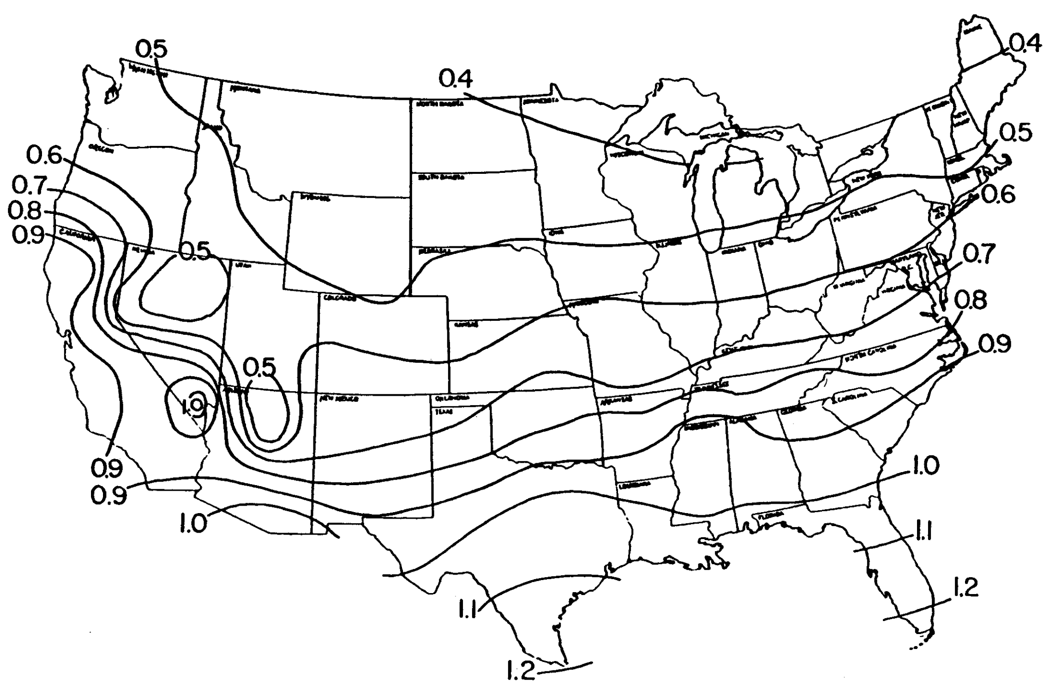


Figure 4. Values of K for the continental United States (from Barth, 1985).

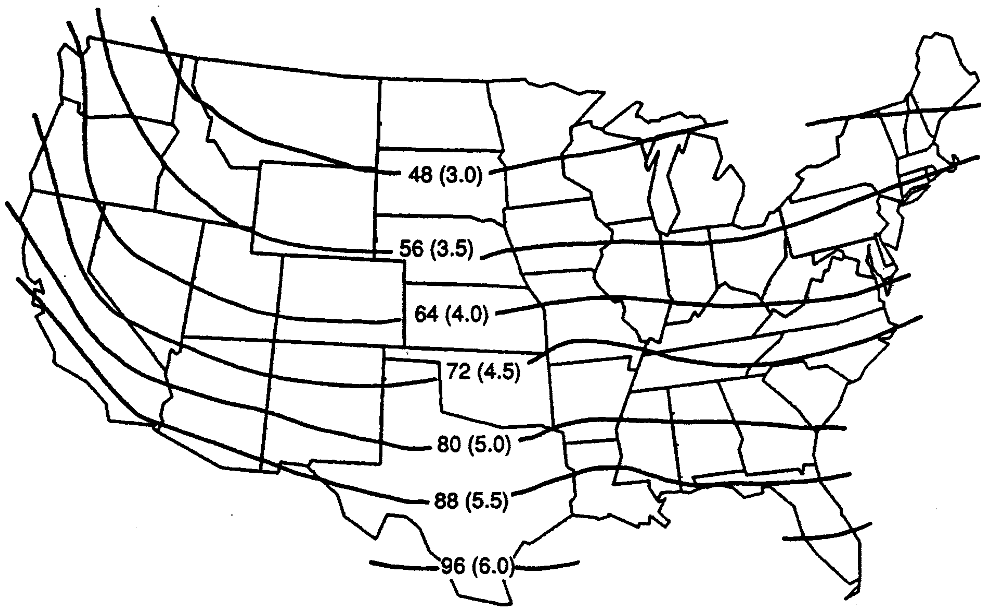


Figure 5. Volumetric organic loading rates in kg VS/1000 m^3-day (lb VS/1000 ft^3-day) for uncovered anaerobic/facultative lagoons, from ASAE Standard ANSI/ASAE EP403.3 JUL99: Design of Anaerobic Lagoons for Animal Waste Management (ASAE Standards, 1999).

Table 1. Sludge accumulation factors from ANSI/ASAE EP403.3 Jul99: Design of Anaerobic Lagoons for Animal Waste Management (ASAE Standards, 1999).

Type of Operation	m^3/kg TS Added	ft^3/lb TS Added
Poultry - Layer	0.00184	0.0295
Poultry - Pullet	0.00284	0.0455
Swine	0.00303	0.0486
Dairy	0.00455	0.0729

continental U.S.. ASAE recommended loading rates roughly correspond to the rational design standard maximum loading rates for poultry and swine lagoons with slight differences caused by simplification of the iso-K lines on the design map.

Sludge storage volume is calculated by multiplying total solids loaded into the lagoon during the desired storage period (may be up to 20 years) by the appropriate accumulation factor shown in Table 1. Effluent storage is calculated by adding volume of waste generated in one year, runoff volume, and washdown water used between pump-out periods and subtracting evaporation during the same period. The ASAE Standard includes a minimum depth equal of 6.6 ft (2 m), and a suggested maximum depth of 20 ft (6 m). Minimum detention time is recommended to be 50 days for a single lagoon cell. A maximum length to width ratio of 4 to 1 is also recommended.

NRCS Design Guidelines for Anaerobic Lagoons

The NRCS Agricultural Waste Management Field Handbook (USDA-NRCS, 1992) gives design guidelines for anaerobic lagoons. The maximum volumetric loading rates recommended by NRCS (Figure 6) are somewhat higher than those recommended by the ASAE Standard, and range from 3 to 7 lb VS/1000ft^3-day (48 to 112 kg/1000 m^3-day) in the continental U.S. The NRCS guidelines advise reducing the rates shown in Figure 6 by 50% in cases where odors must be minimized.

Sludge storage volume is determined using the same sludge accumulation factors as in the ASAE Standard (Table 1). Suggested storage period is 15-20 years. Effluent storage volume consists of the actual volume of manure, flush water, normal precipitation minus evaporation on the lagoon surface, and any fresh water added to the lagoon during the treatment period. Treatment period is defined as the time between land application events.

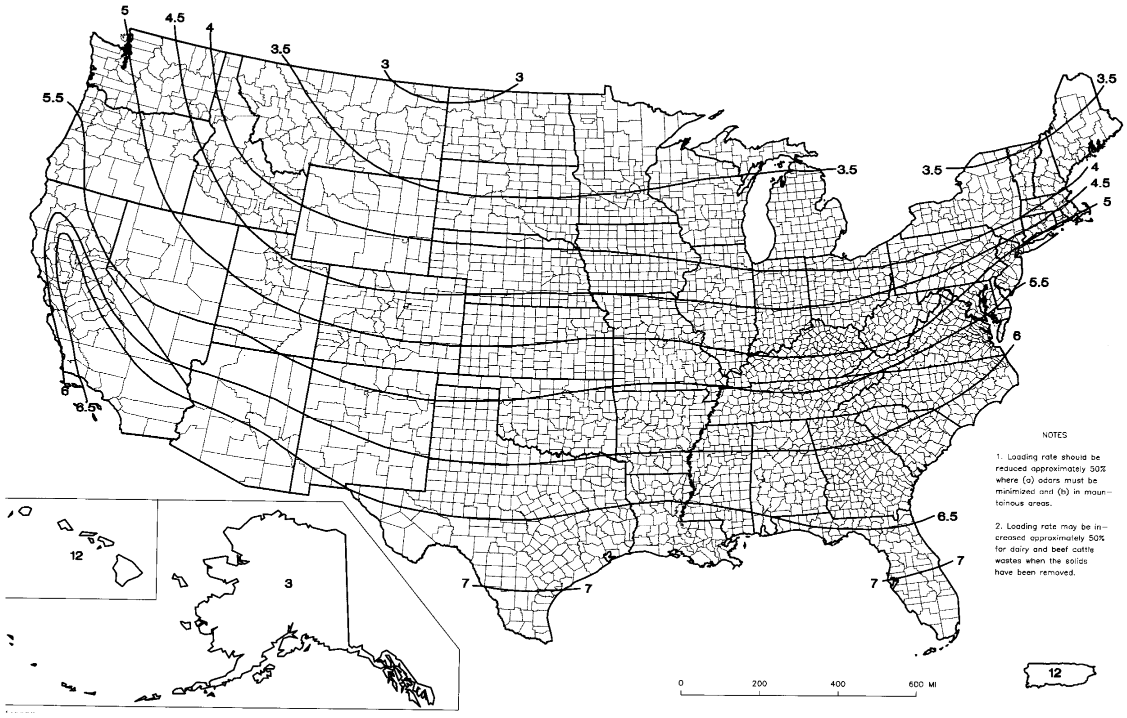


Figure 6. Volumetric organic loading rates in lb VS/1000 ft^3-day for uncovered, anaerobic/facultative lagoons, from NRCS, 210-AWMFH, 4/92 651.1004(a) Anaerobic Lagoons (USDA-NRCS, 1992).

The NRCS guidelines define two operational liquid levels: maximum operating level and maximum drawdown level. Maximum operating level is the top of the effluent storage volume, and maximum drawdown level is the top of the treatment volume as shown in Figures 2 and 3. Maximum drawdown level of the lagoon should be no less than 6 ft (1.8 m), with a 10 ft (3.0 m) minimum depth recommended in colder climates for odor control.

Impermeable Covered Anaerobic Lagoons

Anaerobic lagoons equipped with impermeable covers are designed to maximize methane production, but this criterion may evolve over time to embrace other goals, such as maximizing nutrient capture. The impermeable cover prevents rainfall and oxygen from entering the lagoon, and likewise prevents methane and odors from escaping into the atmosphere. The NRCS proposed a national design standard for covered anaerobic lagoons in 1996 (USDA-NRCS, 1996); however, due to changes within the agency, the national standard was not issued. The now defunct Interim Conservation Practice No. 360 is still considered the state of the art in covered lagoon design, and state NRCS offices are free to adopt it as a design standard.

The proposed guidance (USDA-NRCS, 1996) indicates that a covered anaerobic lagoon should be designed for methane production and recovery. Covered anaerobic lagoons must meet the basic criteria for anaerobic lagoons, with certain modifications. The standard does not provide for effluent storage in the same vessel as the treatment volume; therefore, a covered anaerobic cell is considered to the first cell in a two-cell lagoon. Effluent storage must be contained in a cell downstream from the covered cell. Also, the standard applies only to lagoons with influent manure slurries with less than 2% solids.

Covered lagoons are sized based on volatile solids loading rate and hydraulic retention time (HRT). According to the NRCS interim standard, covered lagoon design should use the larger volume calculated from the two methods based on the maps given in Figure 7. Loading rates for covered anaerobic lagoons range from 4.5 to 12 lb VS/1000ft^3-day (72 to 192 kg/1000 m^3-day) in the continental U.S.. Minimum HRT for methane production, based on an assumed value of 60% VS destruction, range from 35 to 60 days. These retention times are within the range of typical design values for low-rate, unmixed sludge digesters used in municipal wastewater treatment plants.

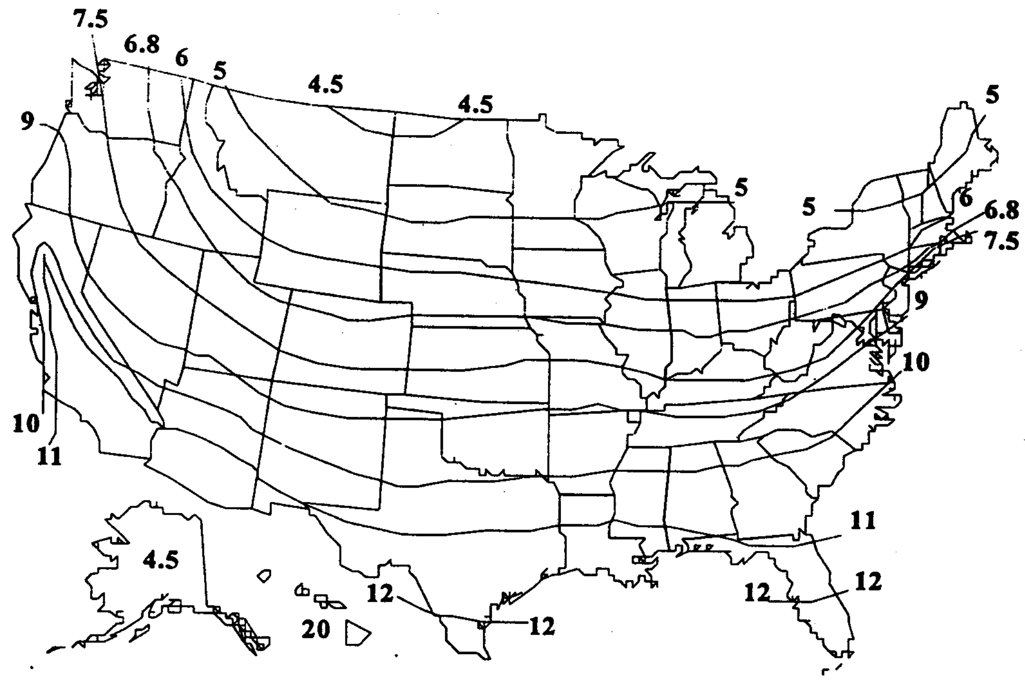


Figure 7a. Volumetric organic loading rates in lbs VS/1000 ft^3-day for covered anaerobic lagoons, from NRCS, NHCP 5/96 Code 360, Interim Conservation Practice Standard: Covered Anaerobic Lagoon (USDA-NRCS, 1996).

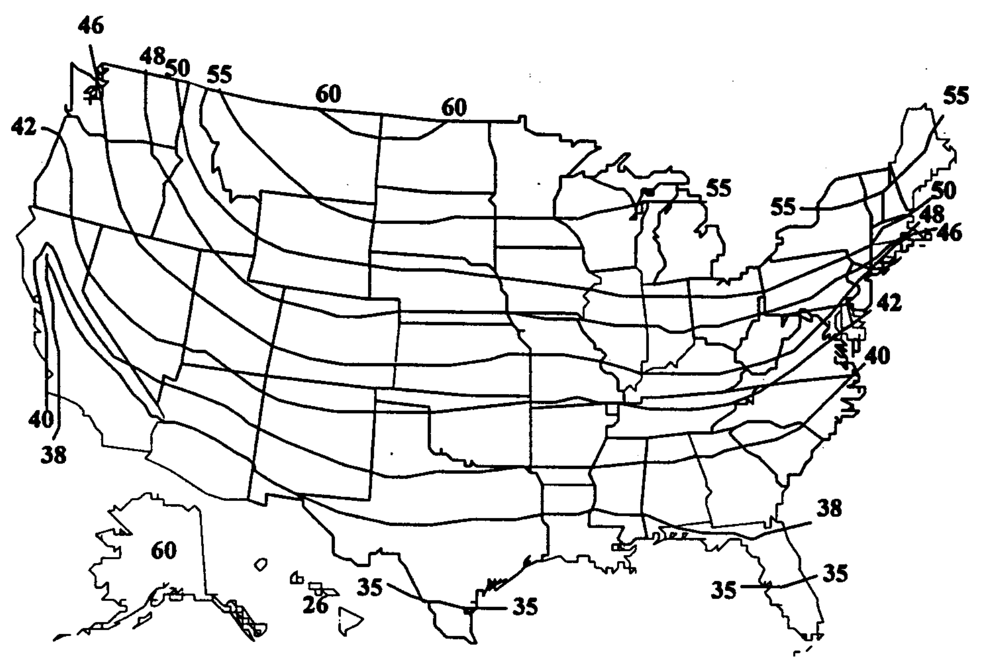


Figure 7b. Minimum hydraulic detention times in days for covered anaerobic lagoons, from NRCS, NHCP 5/96 Code 360, Interim Conservation Practice Standard: Covered Anaerobic Lagoon (USDA-NRCS, 1996).

Naturally Aerated Lagoons

Naturally aerated lagoons, frequently called facultative stabilization ponds or oxidation ponds when used to treat domestic sewage, rely on the presence of an algae to add DO to the system. Two types of design methods are used: surface organic loading rate and the Wehner-Wilhelm equation. Naturally aerated lagoons are relatively shallow, and their reactor type falls somewhere between plug-flow and complete-mix. Due to uncertain mixing regime of a naturally aerated lagoon and the high concentration of suspended solids in influent from animal facilities, naturally aerated lagoons are generally used as secondary or tertiary cells in a multi-cell lagoon system. Primary sludge storage takes place in an upstream, usually anaerobic cell.

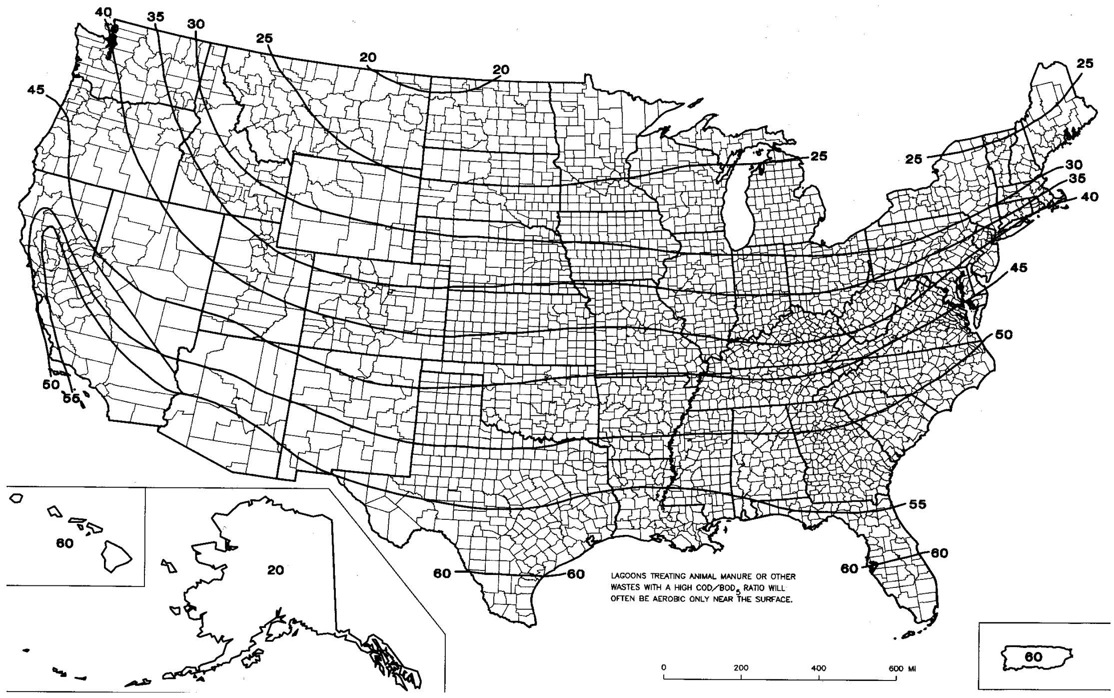


Figure 8. Surface organic loading rates in lbs BOD_5/acre-day for naturally aerated lagoons, from NRCS, 210-AWMFH, 4/92 651.1004(b) Aerobic Lagoons (USDA-NRCS, 1992).

Standard surface organic loading rates for naturally aerated lagoons are based on five-day biochemical oxygen demand (BOD_5) rather than VS. Tchobanoglous and Burton (1991) give recommended surface loading rates of 20 to 60 lb BOD_5/acre-day (56 to 202 kg BOD_5/ha-day), but state that much higher rates have been applied at various locations. Reed, Middlebrooks, and Crites (1988) recommend the following loading rates for aerobic lagoons: 40 to 80 lb BOD_5/acre-day (45 to 90 kg BOD_5/ha-day) in regions where the average winter air temperature is above 15°C; 20 to 40 lb BOD_5/acre-day (22 to 45 kg BOD_5/ha-day) where the average winter air temperature is between 0° and 15°C; and 10 to 20 lb BOD_5/acre-day (11 to 22 kg BOD_5/ha-day) where the average winter air temperature is below 0°C. Acceptable surface loading rates for naturally aerated lagoons built in the continental U.S. according to NRCS guidelines (USDA-NRCS, 1992) are shown in Figure 8, and range from 20 to 60 lb BOD_5/acre-day.

The Wehner and Wilhelm equation (Tchobanoglous and Burton, 1991) solves for organic substrate conversion based on first-order kinetics in a reactor intermediate between a complete-mix and plug-flow regime. The formula has been solved graphically for a range of mixing values (dispersion factors) kinetic coefficients, and detention time (Figure 9).

Facultative stabilization ponds are designed with depths of 4 to 8 ft. Minimum depth of naturally aerated lagoons built to NRCS guidelines (USDA-NRCS, 1992) is 2 ft, and maximum depth is 5 ft.

Mechanically Aerated Lagoons

Mechanically aerated lagoons do not rely on algae, but depend on mechanical aerators to create an aerobic environment in the lagoon. The aerators are also expected to mix the contents of the lagoon. Mechanically aerated lagoons are considered to be complete mixed reactors, and do not include sludge storage. In agricultural settings, they are used either as the first cell in a multi-cell lagoon, or as a downstream cell following anaerobic treatment.

The NRCS design approach for mechanically aerated lagoons uses a standard formula to calculate the aerator capacity to meet oxygen demand based on the field transfer rate of the aerator and the organic loading rate of the lagoon (USDA-NRCS, 1992). NRCS guidelines do not specify limits on lagoon loading. The strategy is to provide sufficient aeration capacity to meet the oxygen demand of any loading to the lagoon. Most aerated lagoons operate at low volumetric loading rates, perhaps 0.6 lb BOD_5/1000 ft^3-day (1 kg BOD_5/1000 m^3-day) or less.

The power requirement for complete mixing of lagoon contents is generally estimated to be within the range of 0.6 to 1.2 hp/1000 ft^3 (16 to 30 kW/1000 m^3) (Tchobanoglous and Burton,

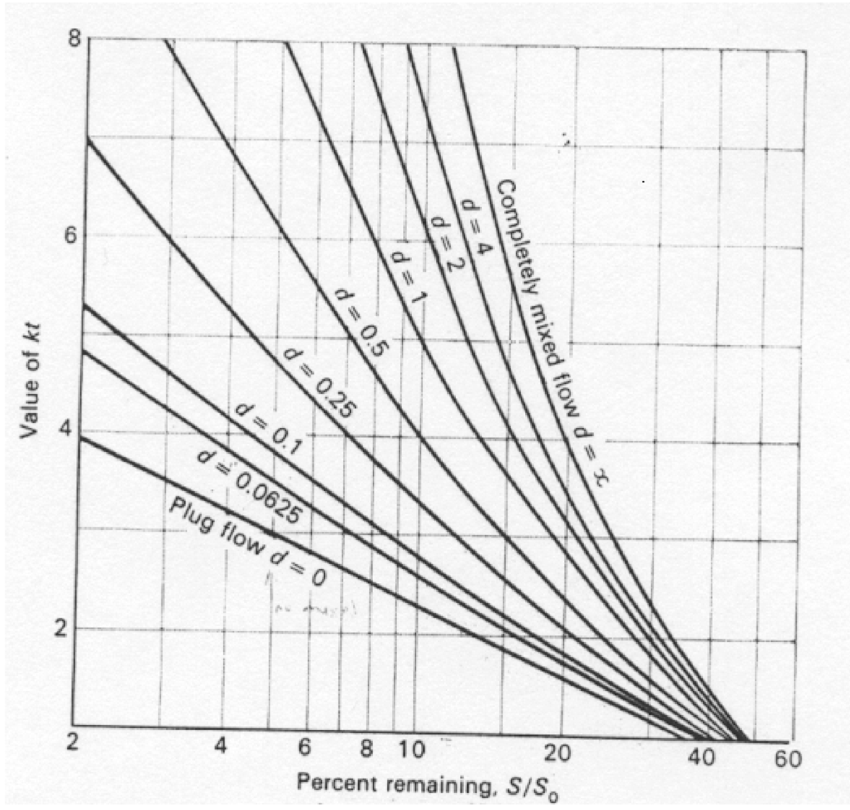


Figure 9. Graphical solution to solve for fraction of organic matter remaining in effluent (S/S^o) using the Wehner-Wilhelm equation, given hydraulic retention time (t), first order reaction constant (k), and dispersion factor (d), from Tchobanoglous and Burton (1991).

1991). The power required for complete mixing is much higher than the aeration requirement for all but the most concentrated organic wastes, and will usually control design. Since aerated lagoons are considered to be completely mixed reactors without sludge settling, they are designed with HRT to achieve the solids residence times necessary for BOD removal (5-10 days) or nitrification (20-30 days).

Aerated lagoons have a large surface area to volume ratio. Depths range from 3 to 10 ft. Lagoons up to 6 ft in depth function as completely mixed units with no solids settling.

Hybrid Anaerobic/Aerobic Lagoons

Recent innovations in lagoon design propose to reduce the odorous emissions from anaerobic/facultative lagoons by creating a quasi-aerobic layer near the surface of the lagoon. The two methods to create this layer are aerating the lagoon surface to a low DO concentration using mechanical aerators, and floating a thick, permeable liner atop the lagoon surface. As of this writing, neither technique has been successfully demonstrated on-farm, nor have design standards been promulgated.

Anaerobic Lagoon with Surface Aeration

Zhang et al. (1997) proposed reducing the odors emitted by uncovered, single-cell anaerobic/facultative lagoons by inducing a thin aerobic zone at the liquid-air interface. Odors emitted from laboratory lagoon columns were significantly reduced using a 0.5 ft layer thickness and 0.5 mg/l dissolved oxygen concentration. The authors propose creating a low oxygen aerobic layer in a farm-sized lagoon using unspecified, mechanical aerators. In theory, aerators floating atop the anaerobic/facultative lagoon will not disturb the sludge storage layer far below the liquid surface; therefore, sludge storage, effluent storage and treatment can all be accomplished in a single-cell lagoon. The practical limitation of this proposed design is selecting an aerator that will simultaneously aerate the surface of the lagoon, leave the sludge storage zone undisturbed, and allow suspended solids to settle to the bottom of the lagoon. This runs contrary to current design practices for mechanically aerated lagoons, in which aerators are chosen to both mix and aerate the lagoon.

Anaerobic Lagoon with a Permeable, Aerobic Cover

The second method of inducing an aerobic zone in an anaerobic lagoon is to cover the lagoon with a thick, permeable liner. Two odor control mechanisms are espoused for this technique: reduction of air exchange between the lagoon surface and the atmosphere, and creation of a biologically active aerobic layer floating atop the lagoon (Miner and Pan, 1995). In theory, liquids wick up into the liner material, creating an attached biological film similar to those found in trickling filters. Aerobic microorganisms living in the attached film digest odorous gases passing through liner. One would expect the designer to approach the two lagoon components separately—designing treatment and sludge storage components along the lines of a covered anaerobic lagoon, and designing the liner to promote an aerobic environment. The cover must be permeable to liquids and gases, yet thick enough to prevent it from sinking into the anaerobic portion of the lagoon. Sludge storage can take place in the covered cell, but effluent storage must be contained in a downstream cell.

BIOLOGICAL COMMUNITIES IN LAGOONS

Degradation of animal manure involves complex interrelated microbial processes of serial and parallel steps (Masse and Droste, 2000). The general trend of treatment in an uncovered anaerobic/facultative lagoon follows the scheme shown in Figure 10. Settleable manure solids fall to the bottom of the lagoon to be broken down into sludge, soluble liquids, and gases. Soluble organic matter enters the treatment process at appropriate points in the scheme. Lagoons contains a number of distinct microbial communities working symbiotically to digest organic material. The extent to which organic matter is degraded depends on the communities present in the lagoon, and to a certain degree, the characteristics of the influent to be degraded. The microbial communities found in lagoons include: anaerobic and facultative heterotrophic bacteria, phototrophic organisms, and aerobic bacteria.

Anaerobic Heterotrophic Bacteria

Three major groups of anaerobic heterotrophs are involved in the digestion of organic waste: hydrolytic bacteria, fermenting and acid-forming bacteria, and methanogenic and sulfate-reducing bacteria. Denitrifying bacteria may be present if nitrate is produced in the lagoon. Generalized reactions carried out by anaerobic bacteria are given in Table 2.

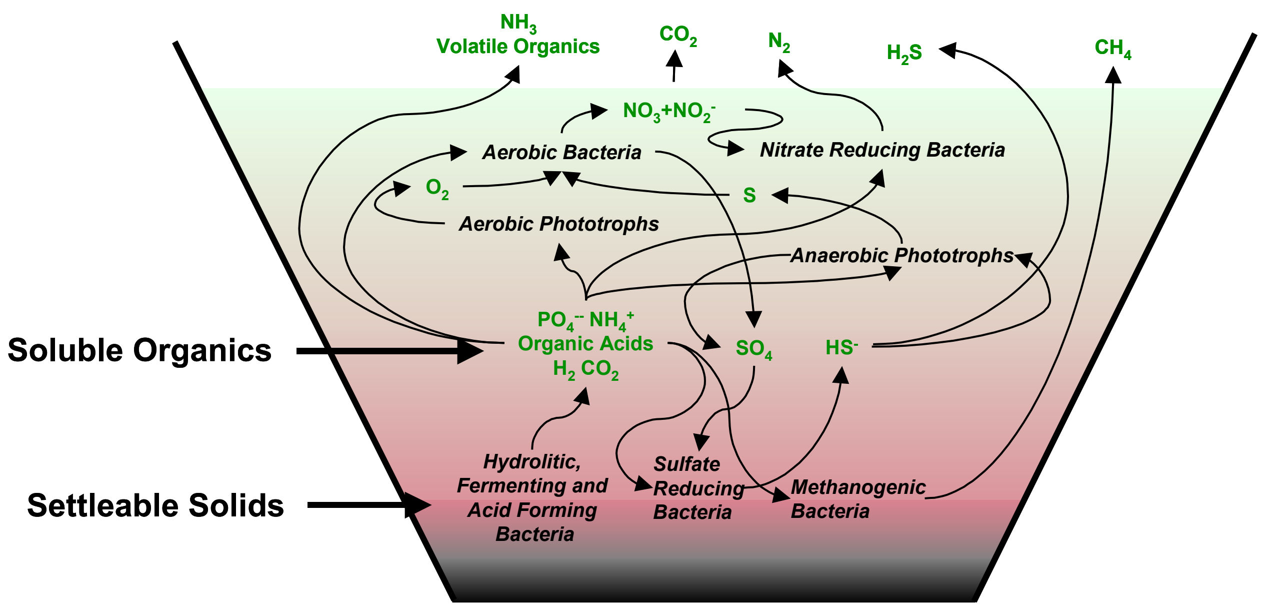


Figure 10. Biological degradation of manure in uncovered anaerobic/facultative lagoons.

Table 2. Generalized reactions of anaerobic heterotrophic bacteria.

Fermentation	Organic-C $\rightarrow$ Simple fatty acids + CO_2 + New Cells
Nitrate Reduction	Organic-C + NO_3^- + $H^+ \rightarrow$ CO_2 + NO_2^-, NO, N_2O, N_2 + New Cells
Sulfate Reduction	Organic-C + SO_4^- $\rightarrow$ CO_2 + H_2S, S^o, HS^- + New Cells
Methanogenesis	Organic-C, HCO_3^-, H_2 $\rightarrow$ CH_4 + CO_2 + New Cells

Hydrolytic Bacteria

Hydrolytic bacteria break down complex biopolymers, such as carbohydrates, proteins, lipids and nucleic acids to their respective soluble monomers. For example, cellulolytic and proteolytic bacteria hydrolyze cellulose and proteins to glucose and amino acids, respectively. The monomers are directly available to the next group of bacteria—the fermenting and acid-forming populations.

Fermenting and Acid-Forming Bacteria

Fermenting and acid-forming bacteria convert monomers to a mixture of alcohols, ketones, volatile fatty acids, succinate, and lactate. In addition, small concentrations of acetate, hydrogen, and carbon dioxide are produced by the proton-reducing acetogenic bacteria such as *Syntrobacter wolinii* and *Syntrophomonas wolfei* (McInernay et al., 1981).

Methanogenic and Sulfate-Reducing Bacteria

Methanogenic and sulfate-reducing bacteria convert acetate, sulfate, hydrogen, and carbon dioxide to methane and hydrogen sulfide, respectively. Sulfate reduction is more favorable energetically than methane production. In the presence of low concentrations of sulfate, methanogens dominate. If organic matter is limited, high concentrations of sulfate may inhibit methanogenesis.

Phototrophic Organisms

A wide range of phototrophic organisms carry out photosynthesis in lagoon layers that allow light penetration. Generalized reactions carried out by various groups of phototrophic organisms are given in Table 3.

Algae

The most common algal species encountered in lagoons are *Chlamydomonas, Euglena, Chlorella, Scenedesmus, Microactinium* and *Oscillatoria* (Bitton, 1994). Algal photosynthesis depends on temperature and light. Algae play a significant role in supporting the growth of aerobic and anoxic bacteria by producing oxygen in daylight. Algae are capable of both heterotrophic and photoheterotrophic growth; therefore, algae play a significant role in organic matter removal (Almasi and Pescod, 1996).

Anaerobic Phototrophic Bacteria

Anaerobic photosynthetic bacteria use H_2S as electron donor instead of H_2O in conversion of CO_2 to cell material. There are approximately 60 species of phototrophic bacteria, broadly grouped into purple and green bacteria (Bitton, 1994). Phototrophic bacteria use CO_2 or volatile fatty acids as a carbon source, light as energy source, and reduced sulfur compounds (H_2S, S°) as electron donors.

Cooper (1962) determined that algae and photosynthetic bacteria always coexist in lagoons. When algae appears to dominate the system, purple sulfur bacteria are also present—only in smaller numbers. Likewise, when purple bacteria dominate, algae are present. The purple or red color of lagoons depends on the presence of reduced sulfur in bacterial chromoplasts.

Aerobic Bacteria

The aerobic layer of facultative lagoons also contains several species of aerobic bacteria that are both autotrophic and heterotrophic in nature. These may include common soil bacteria such as *Arthobacter, Bacillus, Pseudomonas, Escherichia coli, Nitrosomonas, Nitrobacter,* and other sulfur- and iron-oxidizing species. Generalized reactions carried out by aerobic bacteria are given in Table 4.

Table 3. Generalized reactions of phototrophic organisms.

Aerobic	
Algae	$CO_2 + O_2 + H_2O \rightarrow O_2$ + New Cells
Anaerobic	
Purple Sulfur Bacteria	$CO_2 + H_2S, HS^- \rightarrow S^o$ + New Cells
	$CO_2 + S^o + H_2O \rightarrow SO_4^{2-}$ + New Cells
Purple Non-Sulfur Bacteria	Organic-C + $H_2S, HS^-, S^o \rightarrow SO_4^{2-}$ + New Cells

Table 4. Generalized reactions of aerobic bacteria.

Carbon Oxidation	Organic-C + O_2 → CO_2 + H_2O + New Cells
Ammonia Oxidation	NH_4^+ + O_2 + HCO_3^- → NO_2^- + H_2CO_3 + H_2O + New Cells
	NO_2^- + NH_4^+ + H_2CO_3 + HCO_3^- → NO_3^- + H_2O + New Cells

Table 5. Effect of lagoon environmental and operational factors on layer formation.

Factor	Orientation	Effect
Material Flow	Horizontal	Change in lagoon contents from inlet to outlet.
Wind	Vertical	Mixing tangential and parallel to wind direction.
	Horizontal	Winds with, and counter to, the direction of flow may alter hydraulic retention time.
Temperature	Vertical	Thermal layers develop due to heat movement from earth and solar radiation.
Light Penetration	Vertical	Depth of penetration dependent on lagoon albedo and suspended solids.
Oxygen Status	Vertical	Balance between oxygen removal and addition results in greater oxygen concentration near lagoon surface.

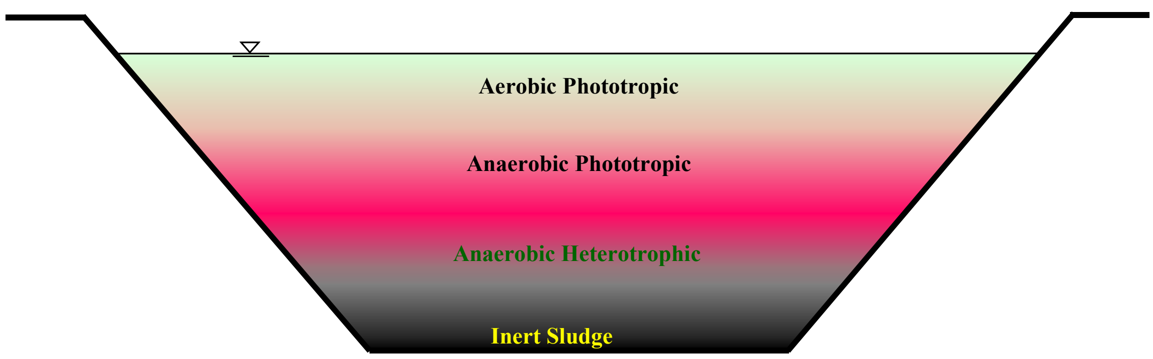


Figure 11. Expected stratification of environmental niches in uncovered anaerobic/facultative lagoons.

Stratification of Lagoon Biota

An implication of Figure 10 is that biological processes leading to the degradation of manure occur in different locations within a lagoon. Five factors (material flow, wind, temperature, light penetration, and oxygen status) tend to break the lagoon into vertical layers and horizontal zones (Table 5) that lead to formation of environmental niches inhabited by distinct biological communities. The overall effect of niche formation is layering of lagoon biota. Figure 11 shows the lagoon layers as they are believed to exist in single-cell, anaerobic/facultative lagoons.

Symbiosis Between Biological Communities

It is important to note that lagoon communities rarely perform their functions in the absence of other communities. Symbiosis between communities of acid-forming bacteria and methanogenic bacteria, acid-forming bacteria and phototrophic organisms, sulfate-reducing bacteria and purple sulfur bacteria, algae and aerobic bacteria, plus ammonia-oxidizing bacteria and nitrate-reducing bacteria are important processes in lagoon treatment.

Acid Formation-Methane Formation/Phototrophic Metabolism

The overriding assumption of early lagoon development was that the symbiosis between acid-forming and methane forming communities was the driving force in anaerobic manure degradation (Hill and Barth, 1974; Barth 1985). Acid-forming bacteria convert the byproducts of hydrolytic bacteria metabolism into fatty acids, and methane formers convert fatty acids to CH_4 and CO_2. If a balance is maintained between acid formation and acid digestion, then there is a thermodynamically positive drive to covert organic solids to CH_4. This assumption is based on the belief that lagoon biology is similar to that of an anaerobic digester (McCarty, 1964a). Purple bacteria are also able to metabolize certain fatty acids to CO_2 (Pfening and Truper, 2001). So, in a lagoon in which phototrophic organisms dominate, the driving force may be conversion of organic solids to CO_2 without production of CH_4. Regardless of whether acids are consumed by a community of methane-formers or purple bacteria, this symbiosis is a good barometer of lagoon health. A lagoon operator is able to prevent upset conditions by monitoring pH and fatty acid concentration and taking appropriate actions as pH begins to drop (McCarty, 1964b).

Sulfate Reduction–Sulfide Oxidation

A similar symbiosis is observed in the sulfur cycles of lagoons. Sulfate-reducing bacteria convert acetate, sulfate, and hydrogen to CO_2 and H_2S. Anaerobic photosynthetic bacteria use H_2S in conversion of CO_2 to cell material. The H_2S can either be oxidized to regenerate sulfate or reduced to elemental sulfur and deposited with cellular material (Table 3). The sulfur cycle can continue whether or not additional sulfate is available to the system. Sulfate is rarely limited in animal waste lagoons since it is a byproduct of protein metabolism, abundant in mammalian urine. This symbiosis is another example of how lagoons may operate beyond the known bounds of methane formation. At low organic loading rates and high sulfate concentrations, sulfate reducing bacteria out compete methane formers for available resources. Their waste product, H_2S, is consumed by purple bacteria, and the process is driven towards conversion of organic matter to CO_2.

Algal Photosynthesis-Aerobic Metabolism

Heterotrophic activity by aerobic bacteria results in the production of CO_2 and micronutrients necessary for the growth of algae. Algae in turn provide oxygen that is necessary for the growth of aerobic heterotrophs. This symbiosis plays the major role in organic matter removal in aerobic systems. Conversion of organic carbon to CO_2 provides the sink that moves all processes towards completion.

Nitrification-Denitrification

Nitrification-denitrification in lagoons is the work of symbiosis between communities of anaerobic-facultative and aerobic bacteria. Understanding this symbiosis is critical in the search to reduce ammonia emissions from lagoons.

A number of heterotrophic bacteria (*Pseudomonas, Thiobacillius denitrificans, Denitrobaccilus, Flavobacterium, Lactobacillus, Micrococcus, Spirilium*, among others) are able to use nitrate as a source of oxygen under anaerobic and anoxic conditions. Organic carbon is consumed, and bicarbonate alkalinity is released during denitrification, acting to raise pH. The final end product of denitrification is N_2 gas; NO and N_2O are gaseous intermediate products of denitrification. The biological oxidation of ammonium to nitrite (*Nitrosomonas, Nitrosococcus, Nitrosocystis)* and nitrate (*Nitrobacter*, *Nitrosocystis*) consumes inorganic carbon and lowers pH. Heterotrophic bacteria quickly denitrify much of the nitrate formed in facultative lagoons. The result of this quick conversion is simultaneous nitrification-denitrification—the process by which ammonia can be converted to N_2 without the apparent production of nitrate. The acidity generated during nitrification is neutralized by denitrification, resulting in a near neutral pH, which is optimum for both systems (Smith and Evans, 1982). Biological nitrification is generally expected to occur in liquids at DO concentrations greater than 1.0 mg/l (Tchobanoglous and Burton, 1991); however, simultaneous nitrification-denitrification has been shown to occur at lower DO concentrations. Svoboda (1995) measured the release of N_2 gas when swine slurry was treated at DO greater than 0.1 mg/l and detention time longer than 2 days. When DO dropped below 0.1 mg/l, nitrogen remained in the form of ammonia —ammonia with the potential to be lost to the atmosphere.

Harper et al. (2000) studied emissions from a four-cell lagoon treating swine waste in Georgia. Gaseous nitrogen losses in the third and fourth, partially aerobic cells appeared to follow conventional pathways of nitrification-denitrification. High concentrations of O_2 and NO_3^- were present near the atmospheric-liquid interface, and significant amounts of N_2 and N_2O were emitted from these cells. The first cell seemed to defy the conventional understanding of nitrification-denitrification. Analysis of gas bubbles collected from the first, anaerobic cell indicated that both N_2 and NH_3 gases were emitted at near equal rates, with no emission of N_2O, nor measurable concentration of NO_3^- in the liquid. The authors suggested N_2 formation takes place in the lagoon due to spontaneous chemical conversion of NH_4^+ to N_2 at an alkaline pH in the presence of Fe^{2+}, or nitrification-denitrification by methanotrophs. The second pathway suggests another, yet unstudied symbiosis between methane formers and methane consumers. Jones et al. (2000) reviewed the literature on nitrogen transformations and concluded that it is clearly possible for the N_2 gas formation in the Georgia lagoons to be biological in nature. They contend that the physical and chemical conditions in lagoons support such transformations.

ANNUAL AND DIURNAL CYCLES OF AGRICULTURAL LAGOONS

The changing seasons of temperate climates have a profound effect on the performance of agricultural lagoons. The combination of seasonal variations in temperature, day length, rainfall, evaporation, and cropping practices creates an annual cycle of liquid accumulation and decline, biological inactivity and hyperactivity, organic matter accumulation and decline. Embedded within the annual cycle are diurnal thermal and chemical cycles. Both annual and diurnal cycles affect circulation and mixing of the lagoon.

Storage

A water year is determined by seasonal variations in the ratio of rainfall to evaporation. Water years in the continental United States typically begin and end in late fall, when storage of ground, soil, and surface water is lowest. Regardless of location, the ability to irrigate lagoon effluent depends on soil moisture condition and the ability of the crop to uptake water and nitrogen. The combined effect of water year and irrigation potential is a seasonal increase and decline in effluent storage volume. This cycle varies greatly with location. Table 6 gives a generalized cycle of effluent storage for the southwestern United States.

Table 6. Annual storage cycle for agricultural lagoons in the southwestern United States.

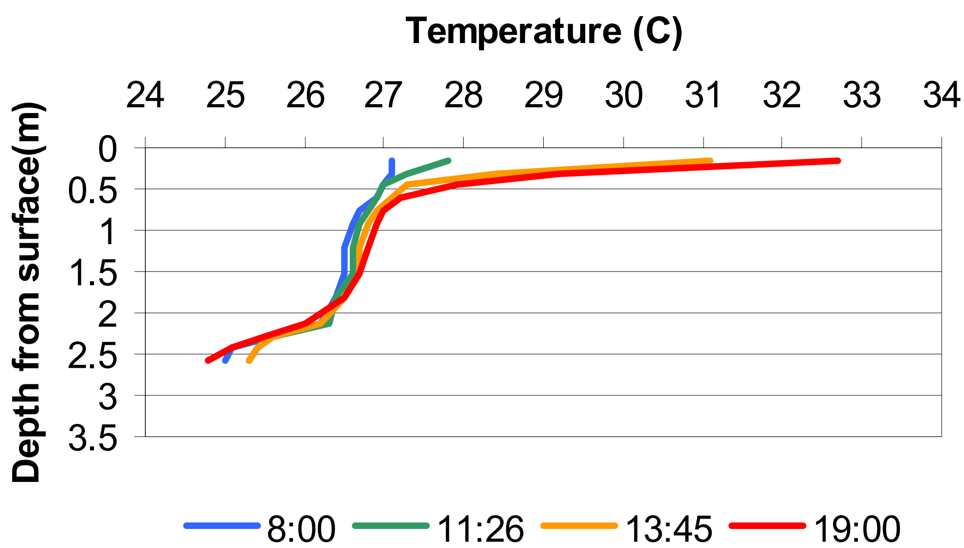
Season	Crops Requiring Water or Nitrogen Input	Rain:Evap.	Combined Effect On Effluent Storage
Late Fall	Few	High	Increasing
Winter	Few	High	Increasing
Early Spring	Cool season grasses Seedbed preparation for corn, sorghum Winter small grains	Decreasing	Reaches maximum operating level
Late Spring to Early Summer	Warm season grasses Corn, sorghum	Low	Decreasing
Late Summer	Seedbed preparation for winter small grains, alfalfa	Low	Decreasing; supplemental water may be needed to maintain treatment volume
Early Fall	Warm and cool season grasses Winter small grains	Increasing	Reaches minimum drawdown level

Thermal

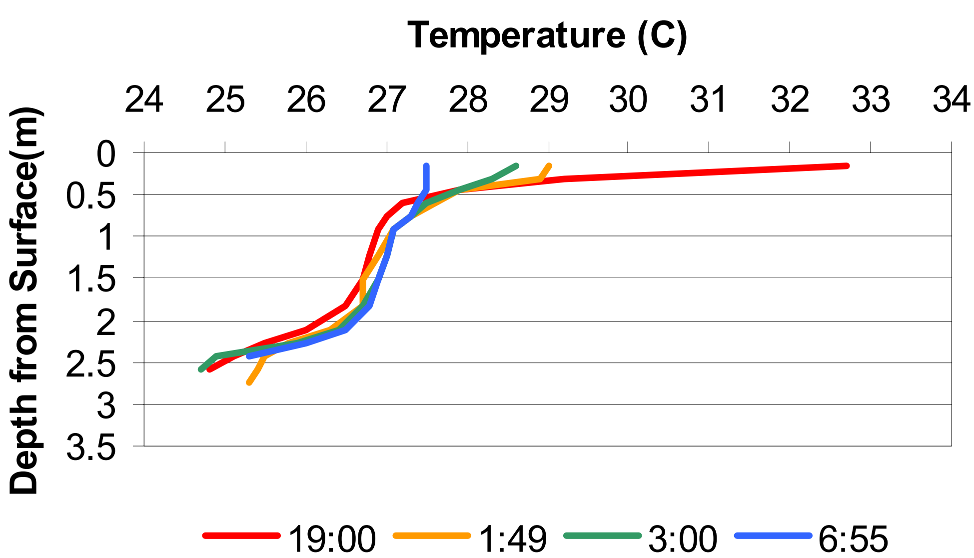
Lagoons in the Northern Hemisphere undergo a period of warming that lasts from January to July, followed by a July to January cooling period. Temperature profiles of naturally aerated lagoons (< 2 m in depth) are generally uniform with depth, and average lagoon temperature follows average monthly air temperature with a slight time lag (Smith and Franco, 1985).

Uncovered anaerobic/facultative lagoons (>2 m in depth) form thermal layers that are defined by the lagoon's daily and annual thermal cycles (Hamilton and Cumba, 2000). Figure 12 shows the daily progression of temperature in swine manure treatment lagoon located at 36°N latitude in Stillwater, Oklahoma. The heating and cooling patterns shown in Figure 12 are typical of clear, windless, summer days. Temperature of the surface layer—within 0.5 to 1.0 m (1.5 to 3 ft) of the lagoon surface—follows a diurnal heating cycle. As shown in Figure 12, it is possible for biota located near the surface of lagoons to experience diurnal changes in temperature exceeding 6°C. The diurnal heating and cooling of lagoons create currents that may cause daily mixing in the upper 2 m (6 ft) of the lagoon.

Early in the morning, temperature is uniform from the surface to 2 m (Figure 12). Below 2 m, the profile tapers to a lower temperature. Figure 13 shows the annual trend of early morning temperatures taken from the same lagoon as Figure 12. The annual trend of early morning temperatures at



Heating: 7:00 am to 7:00 pm



Cooling: 7:00 pm to 7:00 am

Figure 12. Diurnal heating and cooling cycle of a single-cell swine waste treatment lagoon located at 36° N latitude in Stillwater, OK on July 23-24, 1997. (Total depth of lagoon was 3.3 m at time of sampling. Sludge layer of lagoon was approximately 1 m thick.)

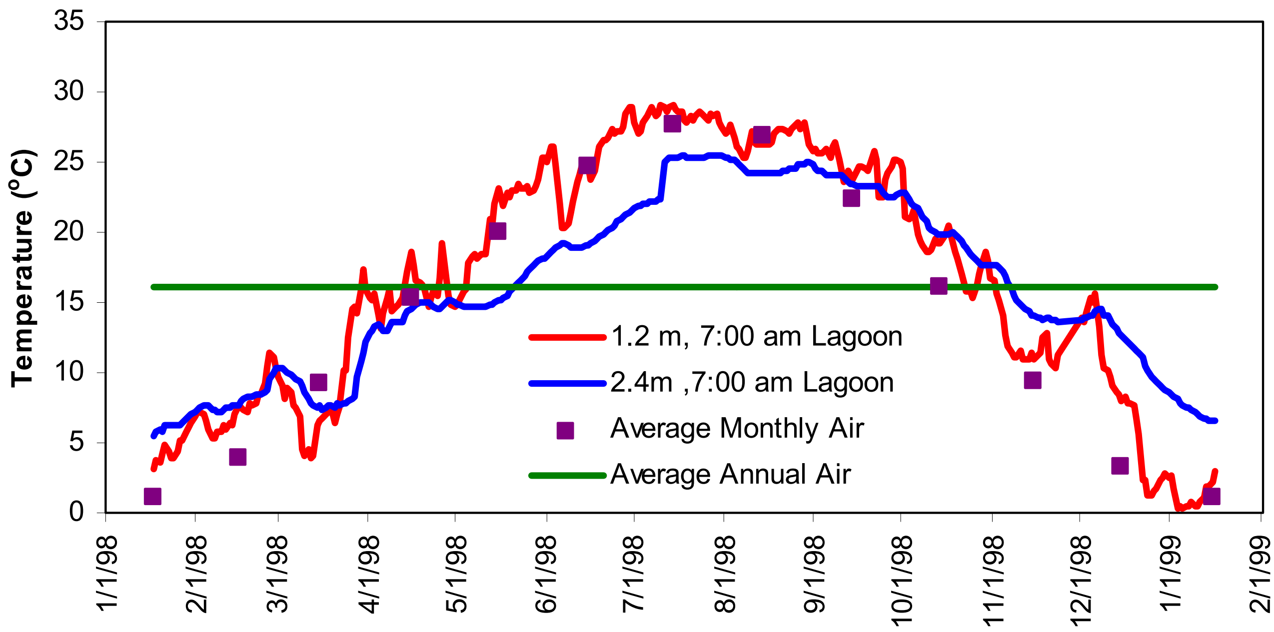


Figure 13. Annual heating and cooling cycle of a single-cell swine waste treatment lagoon located at 36° N latitude in Stillwater, OK. (Total depth of lagoon ranged from 2.75 to 5 m during the time of study. Sludge layer of lagoon was approximately 1 m thick.)

1.2 and 2.4 m suggest the lagoon is divided into two layers. The upper layer follows the same annual trend as shallow lagoons – average temperature follows the monthly average with a slight time lag. The annual thermal cycle of lower layer centers on the mean annual temperature. The lower layer's thermal cycle is less extreme and lags behind the upper layer's cycle.

Seasons in lagoons can be described in this way: summer is when the upper layer is warmer than the lower layer; winter is when the upper layer is cooler than the lower layer. Thermal layers are distinct and unmixed during the winter (12/15 to 2/15 in Figure 13) and summer (5/1 to 9/15 in Figure 13); however, the layers may mix as the early morning temperature of the upper and lower layers approach unity in the spring and fall. Lagoons do not necessarily "turn over" as is common in temperate climate lakes. It is more correct to say that lagoon layers experience prolonged periods of instability in the spring and fall (Hamilton and Cumba, 2000).

Biological Activity

The amount of food available to lagoon microorganisms undergoes an annual cycle in temperate climates. Biological activity depends on temperature; thus, organic matter accumulates in the lagoon during the cool winter months. Warmer temperatures and an excess food supply create a period of biological hyperactivity in the spring. The spring hyperactivity occurs during a period of layer instability, which creates a noticeable increase in odors.

Performance of shallow lagoons and the upper layer of deep lagoons depend upon the activity of phototrophic organisms. Seasonal variations in day length and ice cover may exacerbate the biological activity cycle.

Dissolved Oxygen

Surface aeration and the light reaction of aerobic photosynthesis add O_2 to lagoon liquids. The dark reaction of aerobic photosynthesis and aerobic respiration remove O_2. The equilibrium of factors adding and removing O_2 determines DO concentration at any time and depth. Aerobic and facultative lagoons undergo diurnal DO cycles. DO is lowest at dawn and increases with prolonged exposure to daylight as the light reaction of aerobic photosynthesis adds O_2 to the system. It is possible to see supersaturated concentrations of dissolved oxygen in aerobic lagoons as shown in Figure 14. DO declines at night when aerobic photosynthesis no longer adds O_2. Most agricultural lagoons will return to anaerobic conditions before dawn if the lagoon remains biologically active (Figure 14).

DO equilibrium undergoes an annual cycle created by cycles of organic matter accumulation and day length. A scheme for annual cycles of biological activity, organic matter accumulation, and DO equilibrium for lagoons located in temperate climates is proposed in Table 7.

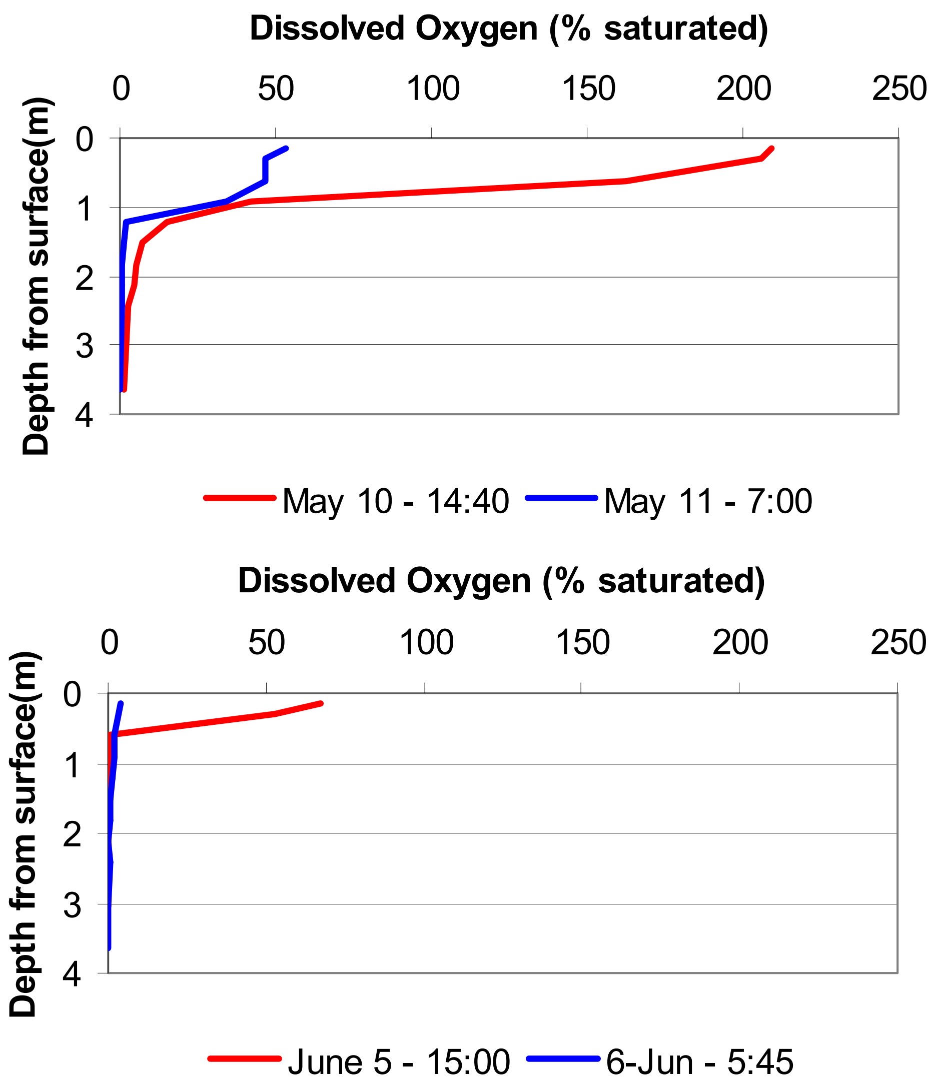


Figure 14. Dissolved oxygen saturation measured during late spring-early summer, 1995 in the second cell of a swine waste treatment lagoon located at 36° N latitude in Jackson, TN. (Total depth of lagoon was 3.9 m on May 10-11, and 4.2 m on June 5-6. No discernable sludge layer was recorded.)

Table 7. Proposed scheme for annual biological activity and oxygen cycles in temperate climate lagoons.

Season	Day Length	Biological Activity	Organic Matter	Dissolved O_2 Balance
Winter	Minimum	Minimum	Increasing	Surface aeration dominant
Spring	Increasing	Increasing	Maximum	Removal by aerobic heterotrophs dominant
Summer	Maximum	Maximum	Decreasing	Aerobic photosynthesis dominant
Fall	Decreasing	Decreasing	Minimum	Transition from photosynthesis to surface aeration as dominant force

EFFECT OF FARM SIZE ON LAGOON DESIGN

Table 8 lists five alternative lagoon designs based on the standards and criteria given in the Agricultural Lagoon Design section. All lagoons were designed as if they were located in the southeastern corner of the state of North Carolina, and designed to treat and store manure generated by a swine finishing building with the capacity to house 960 animals. Waste input was determined using data given in the Agricultural Waste Management Field Handbook Chapter 4 (USDA-NRCS, 1992). Key design parameters were organic loading rate and depth. Lagoons were designed to store 15 years of accumulated sludge according to the generation rates shown in Table 1. Effluent storage is sufficient for three-fourths of the volume needed to recycle nutrients to crops, assuming a plant available nitrogen concentration of 2 lbs/1000 gallons (240 mg/l). Daily influent volume (and therefore, HRT) was determined assuming recycled lagoon effluent was used to remove manure from the buildings and total solids concentration of slurry leaving the buildings was 0.5% by weight. It was assumed each lagoon was constructed with a 2:1 length to width ratio and 3:1 embankment slope. If the lagoons were designed by Barth's (1985) low odor volumetric loading rate, their volume at maximum drawdown level would be 200,000 ft^3.

Table 8 illustrates the difference in lagoons designed to promote the growth of algae and those that rely on anaerobic heterotrophs and phototrophs to degrade manure. There is a jump in surface area from 1.4 to 5.3 acres between lagoons designed by NRCS standards for low-odor anaerobic and naturally aerated lagoons.

Table 8. Comparison of single-cell lagoons for a 960-head swine finishing facility in southeastern North Carolina with 15 years sludge storage, 140,000 ft^3 effluent storage, 2,400 ft^3 per day influent volume, 2:1 length to width ratio, and 3:1 embankment slopes.

	NRCS Guidelines for Anaerobic Lagoon (NRCS, 1993)	**ASAE Standard for Anaerobic Lagoon (ASAE, 1999)**	**NRCS Guidelines for Anaerobic Lagoon with 50% Loading (NRCS, 1993)**	**NRCS Guidelines for Naturally Aerobic Lagoon (NRCS, 1993)**	**Facultative Waste Stabilization Pond (Reed, 1988)**
Depth (ft) at Maximum operating level - Maximum drawdown level	***14**** - 11	***14**** - 11	***14**** - 11.5	***5.0**** - 4.5	***5.0**** - 4.75
Total volume (ft^3) at Maximum operating level Maximum drawdown level	450,000 310,000	490,000 350,000	565,000 425,000	1,090,000 950,000	1,400,000 1,260,000
Estimated depth of sludge (ft)† after 15 years of operation	8	7.5	6.5	-	-
Surface area (acres) at Maximum operating level – Maximum drawdown level	1.15 - 0.95	1.2 - 1.0	1.4 - 1.2	5.3 - 5.25	6.7 - 6.6
Surface area/volume (ft^2/ft^3) at Maximum operating level – Maximum drawdown level	0.11 - 0.13	0.11 - 0.12	0.11 - 0.12	0.21 - 0.24	0.20 - 0.23
Volumetric loading rate‡ (lbs VS/1000 ft^3-day) at Maximum operating level – Maximum drawdown level	2.7 - ***6.0****	2.3 - ***4.5****	1.85 - ***3.0****	0.76 - 0.90	0.56 - 0.64
Surface loading rate (lbs BOD_5/Acre-day) at Maximum operating level – Maximum drawdown level	230 - 280	220 - 260	190 - 220	49.5 - ***50****	39 - ***40****
Hydraulic retention time[3] (days) Maximum operating level – Maximum drawdown level	100 - 46	120 - 63	150 - 94	370 - 310	500 - 440
Mixed layer hydraulic retention time (days) Maximum operating level – Maximum drawdown level	100 - 77	98 - 82	110 - 98	370 - 310	500 - 440

*Key design parameters. †Using sludge accumulation factors of ASAE (ASAE Standards, 1999). ‡At 15-year sludge accumulation level.

Modern swine finishing facilities may consist of 10 or more buildings the size of those used to design the lagoons shown in Table 8. Table 9 lists design alternatives for a lagoon serving a 9,600-head finishing farm located in southeastern North Carolina. Only anaerobic and low-odor anaerobic lagoons were considered, since algae-based treatment would require surface areas up to 70 acres. In an attempt to limit lagoon surface area to less than seven acres, maximum operating level was set at the ASAE Standard's maximum of 20 ft, sludge storage was reduced to 10 years, and effluent storage was based on 3 lb plant available nitrogen/1000 gal (360 mg/l). Higher effluent nitrogen concentrations are reasonable in the deeper lagoons due to conditions discussed in the effect of design parameters on biological communities section. If the lagoons were designed by Barth's (1985) low odor volumetric loading rate, their volume at maximum drawdown level would be 2,000,000 ft^3.

As long as volumetric organic loading rate is the sole parameter determining lagoon design, size of lagoon is directly proportional to size of farm. Many of the problems associated with liquid manure handling systems—atmospheric emissions, liner seepage, and catastrophic failures—are exacerbated in large lagoons.

Table 9. Comparison of single-cell anaerobic lagoon sizes for a 9,600-head swine finishing facility located in southeastern North Carolina, with 10 years sludge storage, 1,000,000 ft^3 effluent storage, 24,000 ft^3 per day influent volume, 2:1 length to width ratio, and 3:1 embankment slopes.

	NRCS Guidelines for Anaerobic Lagoon (NRCS, 1993)	**ASAE Standard for Anaerobic Lagoon (ASAE, 1999)**	**NRCS Guidelines for Anaerobic Lagoon with 50% Loading (NRCS, 1993)**
Depth (ft) at Maximum operating level - Maximum drawdown level	**20*** - 14.25	**20*** - 15.5	**20*** - 15.5
Total Volume (ft^3) at Maximum operating level Maximum drawdown level	3,400,000 2,400,000	3,800,000 2,800,000	4,550,000 3,500,000
Estimated depth of sludge (ft)† after 15 years of operation	9.25	8	7.5
Surface Area (acres) at Maximum operating level - Maximum drawdown level	5.2 - 4.4	5.7 - 5.1	6.8 - 6.1
Surface area/volume (ft^2/ft^3) at Maximum operating level - Maximum drawdown level	0.067 - 0.80	0.065 - 0.079	0.065 - 0.075
Volumetric loading rate[3] (lbs VS/1000 ft^3-day) at Maximum operating level - Maximum drawdown level	3.2 - ***6.0****	2.7 - ***4.5****	2.1 - ***3.0****
Surface Loading Rate (lbs BOD_5/Acre-day) at Maximum operating level - Maximum drawdown level	510 - 600	460 - 520	390 - 430
Design hydraulic retention time‡ (days) Maximum operating level - Maximum drawdown level	87.5 - 54	100 - 71	140 - 100
Mixed layer hydraulic retention time (days) Maximum operating level - Maximum drawdown level	52 - 44	62 - 56	74 - 66

*Key design parameters. †Using sludge accumulation factors of ASAE (ASAE Standards, 1999). ‡At 15-year sludge accumulation level.

Mass of atmospheric emissions is equal to unit emission rate times surface area. If it is assumed that unit emission rate of odorants is proportional to surface loading rate, one would assume by observing Tables 8 and 9 that the volume of odors emanating from the large farm lagoon would be greater than those emitted by the smaller farm lagoon. The lagoon built by NRCS anaerobic lagoon guidelines to treat waste produced by 960 hogs has a maximum surface area of 1.15 acres and an organic loading rate of 230 lbs BOD_5/acre-day (Table 8). The lagoon built using the same guidelines for 9600 hogs has a maximum surface area of 5.2 acres and an organic loading rate of 510 lbs BOD_5/acre-day (Table 9).

Volume of seepage through liners is a factor of liner area, thickness, and depth of liquid above the liner. The lagoons in Table 9 are both larger and deeper than those in Table 8. Seepage volume will be much greater unless liner thickness is likewise increased with the larger farms. Although effluent characteristics may be similar between the lagoons shown in Tables 8 and 9, the fact that the lagoons in Table 9 have seven to nine times the volume of those in Table 8 suggest the larger farm will pose a greater threat to the environment if its lagoon is breached.

EFFECT OF DESIGN PARAMETERS ON BIOLOGICAL COMMUNITIES

In the previous section, we worked within the framework of ASAE Standards and NRCS guidelines to make anaerobic lagoons fit for small and large farms. Performance of lagoons depends on the interaction of a number of related parameters. In essence, the well-being of a biological community depends on unrestricted access to food and nutrients, ability to reproduce, and the presence of environmental conditions to which the community is well adapted.

Organic Loading Rate

Very little data is available in the scientific literature to relate lagoon organic loading rate to the presence of specific biological communities. Some inferences can be made from the years of experience contained in Tables 8 and 9, however.

The rational design standard (Barth, 1985) loading rates are based on the activity of acid-forming bacteria; therefore, we can assume that active communities of heterotrophic bacteria are present when liquid volume is greater than the treatment volume of lagoons designed according to ASAE Standards (which most closely match the rational design standard), provided lagoon temperature remains above 5°C. Also, since all the lagoons in Tables 8 and 9 exceed the rational design standard's minimum volumes for low odors, we may assume they have active communities of methanogenic bacteria reducing volatile organic acid concentrations when temperature exceeds 15°C.

It is logical to associate phototrophic activity with surface loading rate. The breakpoint between algae-based lagoons and lagoons dominated by anaerobic phototrophic bacteria must lie somewhere between the anaerobic/facultative lagoon design (~250 lb BOD_5/acre-day) and naturally aerated lagoon design (50 lb BOD_5/acre-day). Anaerobic phototrophs can out-compete aerobic phototrophs at higher loading rates (Cooper, 1962), but a definitive range of loading rates for purple sulfur and non-sulfur bacteria dominated lagoons has not been identified.

The actual daily organic load on a single-cell agricultural lagoon falls within a range of values that depend on the lagoon's age, the size and number of animals contributing waste to the lagoon, and place in the lagoon's annual storage cycle. The loading rates used to design the lagoons shown in Tables 8 and 9 were calculated at the end of the sludge storage period; therefore, volumetric loading early in the lagoon's design life may be considerably lower than those shown. The lagoons listed in Tables 8 and 9 were designed based on a mean hog size of 113 pounds. Had the buildings been operated as all-in-all-out facilities (that is, each building is stocked with nursery pigs that grow as a group until they reach market weight), the lagoons at the end of the grow-out cycle would be loaded at a rate 2.5 times higher than they were at the beginning (Hamilton et al., 1996).

Standard loading rates are based on treatment potential over the entire year, assuming biota will compensate for the inactivity of cold days later in the season. The actual mass of food available to biological communities on any day is the organic matter added that day—plus organic matter accumulated from previous days. Hence, the food to microorganism ratio after a long winter may be considerably higher than that in late summer. This will cause shifts in the balance of the acid-forming/acid-metabolizing, sulfate-reducing/sulfide-oxidizing, oxygen-producing/oxygen-consuming, and nitrification/denitrification symbioses.

Hydraulic Retention Time

If good settling conditions are maintained in the lagoon, solids retention time and, therefore, the residence time of heterotrophic bacteria living in the active sludge layer of agricultural lagoons can approach the sludge storage period of the lagoon. The residence time of biological communities suspended above the sludge layer is determined by HRT. If the HRT is shorter than the time needed for the communities to reproduce and grow, the communities will be “washed out” of the lagoon. HRT also has an effect on the ability to control pathogenic organisms. The longer pathogens are retained in the lagoon, the more likely they are to “die off” due to competition with the dominant, manure treatment communities.

Lagoon design HRT, defined as total liquid volume of the lagoon divided by daily influent volume, is a range of values as indicated in Tables 8 and 9. The mixed layer HRT shown in Tables 8 and 9 assumes that only the upper 6 ft of the lagoon contributes to volume of a mixed reactor. Completely suspended organisms entering the lagoon will not settle to depths lower than 6 ft, thus the lower layer should not be included in calculating flow through HRT.

The actual HRT can be considerably less than the design values due to flow short-circuiting. An in-depth study of facultative stabilization ponds by Finney and Middlebrooks (1980) concluded that secondary discharge standards were violated frequently, even though applicable state standards for organic loading and HRT time were met. The authors studied four lagoon systems located in New Hampshire, Mississippi, Kansas, and Utah, for a year. Data from the four lagoon sites were analyzed by several empirical and rational design procedures, none of which adequately modeled actual performance. The authors concluded that prediction of pond performance might be enhanced most by improving the understanding of factors affecting actual HRT.

Construction details, such as baffling and inlet and outlet arrangements, affect HRT. Logically, inlets should be placed as far away from outlets (overflow, irrigation, recycling) as possible to minimize short-circuiting. Increasing depth has not been shown to affect BOD removal rates of facultative stabilization ponds (Clark et al., 1970; Pearson et al., 1995). This may be explained by the fact that the actual mixed layer of lagoons is limited to 6 ft regardless of total depth.

Environmental factors, such as wind speed and direction, also have a great effect on actual HRT. Wind speed has been shown to reduce design HRT of lagoons by short-circuiting flow. Modeling studies by Fares and Lloyd (1995) reported a decrease in design HRT to an actual HRT of a few hours with a 2 m/s wind.

Depth

Although the NRCS guidelines (USDA-NRCS, 1992) state that lagoons should be made as deep as possible in cold climates for odor control, the primary function of depth as a design parameter is vertical segregation of biological communities as shown in Table 5 and Figure 11.

Light penetration is of particular importance to phototrophic organisms. The ability of light to penetrate lagoon liquids depends on suspended solids concentration; therefore, it is important to keep sludge storage and the phototrophic treatment zones separated. Assuming that the upper 6 ft (1.8 m) of the lagoon is completely mixed suggests that the depth of the minimum treatment volume should be greater than 6 ft in order to keep sludge solids from potentially entering the phototrophic layer. The lagoons shown in Table 8 will experience a reduction in light penetration and photosynthetic activity before the expected 15 years sludge storage is reached. After 15 years, only 3 ft will separate the maximum drawdown level from the top of sludge storage in the anaerobic lagoon designed by NRCS guidelines (Table 8), resulting in a higher concentration of suspended solids near the surface as sludge solids are scoured into the mixed layer.

Surface Area to Volume Ratio

Comparing Tables 8 and 9 demonstrates the effect of altering the depth of anaerobic lagoons designed using volumetric organic loading rate. Surface loading of the larger, deeper lagoons (Table 9) is twice that of the smaller, shallower lagoons (Table 8). Similarly, surface area to volume ratio, and mixed layer HRT are much lower in the deep lagoons than the shallow lagoons. Changing these parameters may have a dramatic effect on photosynthetic activity, atmospheric emissions, and effluent quality. Sievers et al. (2000) demonstrated that ammonia emission rate of laboratory lagoon columns decreases as surface area to volume ratio decreases. Their study showed that decreased ammonia emissions resulted in higher effluent ammonia-N concentrations. Effluent ammonia-N concentrations were greater than 1000 mg/l in lagoons with surface area to volume ratio in the 0.06 to 0.08 ft^2/ft^3 (0.20 to 0.26 m^2/m^3) range, and concentrations of 300 to 400 mg/l in lagoons with surface area to volume ratio in the 0.10 to 0.15 ft^2/ft^3 (0.33 to 0.38 m^2/m^3) range.

Aeration Level

Zhang et al. (1997) showed that odors emitted by a laboratory lagoon column loaded according to ASAE Standards could be significantly reduced by mechanically aerating the column so that dissolved oxygen concentration in the upper 0.5 ft reached 0.5 mg/l. They concluded that the greatest effect of aeration was oxidation of volatile organic compounds and hydrogen sulfide. Ammonia emissions were not affected at column dissolved oxygen concentrations less than 2.0 mg/l. Humenik et al. (1975) provide a description of a two-stage system at a hog farm incorporating a primary aerated cell (2300 lb BOD_5/1000 ft^3-day) and a naturally aerated second cell (approximately 50 lb BOD_5/1000 ft^3-day). The mechanically aerated cell showed measurable DO (0.2 to 0.8 mg/l) to a depth of 3 to 4 ft, while supernatant COD was on the order of 9,000-10,000 mg/L. A sludge zone was apparent, with COD in the bottom 1.5 to 2 ft of the 8-ft deep lagoon averaging over 60,000 mg/L. The un-aerated cell had a similar sludge zone and also showed measurable DO to a depth of 3 to 4 ft, but supernatant COD was only in the range of 700-800 mg/L in the aerobic surface zone.

Multiple Lagoon Cells

It is a commonly observed phenomenon that multi-cell lagoons perform better than single-cell lagoons (Schneider, 1990). Multiple lagoon cells give greater control of suspended and settled solids. Finney and Middlebrooks (1980) suggest performance of naturally aerated lagoons can be improved by operating a number of cells in series, thus controlling HRT. Mathavan and Viraraghavan (1991) determined that BOD and solids removal efficiencies were not significantly improved by longer detention times in a single cell, but significant improvement was achieved when several cells were operated in series. Another advantage of multiple lagoon cells is that the treatment process can be divided separated into a series of steps controlled by environmental conditions and biological communities. Sobsey et al. (2002) suggest that greater pathogen die-off can be achieved by operating lagoon cells as “multiple chemostats in series.”

EFFECT OF LAGOON OPERATION ON BIOLOGICAL COMMUNITIES

The strength of lagoons is ease of operation. Once the lagoon biota has stabilized, all an operator has to do is maintain a proper water balance, feed the lagoon consistently, maintain earthwork, and periodically check sludge accumulation.

Start-Up

New lagoons started in late spring or early summer mature quickly, because the lagoon biota is established during the most biologically active time of the annual cycle. Filling the lagoon to at least half the treatment volume with water before adding manure also ensures that microorganisms have the proper environment to begin growing. Seeding with sludge and liquids from a properly operating lagoon helps to begin treatment quickly. As a better understanding of lagoon biota is gained, it will be possible to create starter cultures tailored to meet the desired treatment effect and influent characteristics. Use of starter cultures may become routine as biosecurity measures prevent transfer of seed sludge from one farm to another.

Water Balance

Lagoons are not waste disposal repositories. Similar to animal digestive systems, material must flow through the manure handling system for them to function properly. Blocking the flow for an extended period results in accumulation of toxic materials to the detriment of lagoon biota.

Experience over the course of many water years will dictate the steps necessary to maintain lagoon liquids between maximum operating and drawdown levels. A rudimentary water balance is implied in the design standards. In practice, effluent storage capacity is usually based on daily inflow and monthly averages of rainfall and evaporation during the critical storage period (October to

May for the area described in Table 6). It is possible to perform a more precise balance based on historical or statistical climatic information. Cumba and Hamilton (2002) developed a daily time step water balance model that uses information generated by a weather network in Oklahoma. The model can be adapted to other areas if accurate measurements of solar radiation, relative humidity, wind speed, and temperature are available. The Oklahoma model may be used to simulate operation of existing lagoons using data from actual water years, or statistically generated years. Kansas State University has also developed a water balance model that requires estimation of pan evaporation on-site (Ham and DeSutter, 1998).

Feeding

Unless animal numbers are changed, influent characteristics are modified by pretreatment, or the size of the lagoon is altered, the volumetric or surface loading rate remains within the range set during construction. The operator has control over feeding frequency, influent placement and to some extent, influent dilution.

Conventional practice suggests constant feeding of organic matter into the reactor creates a more consistent process. Continuous feeding is not always possible because of removal of waste from buildings depends on periodic flushing or scouring of pits. Little information is available on the advantages of feeding lagoons from the top or from the bottom. A compromise that seems advantageous is to allow soluble material to enter in a phototrophic environment while solids settle into an anaerobic heterotrophic zone.

For optimal performance, feeding amount, frequency, placement, and timing should be tuned to promote healthy microbial communities. Improving performance may involve judicious use of pretreatment, aeration, temporary covers, and liquid level adjustment fine-tuned to the lagoon's annual cycle.

Sludge Removal

Current design standards dictate that solids be removed before sludge encroaches upon liquid treatment volume. The only way for an operator to know the status of sludge in the lagoon is through annual inspection. The operator should measure sludge thickness at the same time each year in order to avoid confusion caused by the annual cycle of organic matter accumulation and decline. Once sludge has filled the allotted storage volume, the operator has two options for removal: complete removal through agitation or dredging, or partial removal with effluent irrigation.

CONCLUSIONS

The level of treatment to be expected from agricultural lagoons is degradation of raw manure into stable sludge and effluent without creation of excessive emission of odors and ammonia. Agricultural lagoons, working alone, will not produce effluent of sufficient quality to be discharged directly into surface or ground water.

Current guidelines break agricultural lagoon volume into three components: sludge storage, effluent storage, and treatment volume. As long as treatment volume is based on daily volumetric organic loading, lagoon size will be dictated by farm size. Many of the environmental problems associated with liquid handling systems—atmospheric emissions, liner seepage, catastrophic failures—are increased when lagoon size is increased. Environmental risk criteria must be investigated to determine what is the appropriate size farm to use lagoon technology. Design parameters must be optimized to ensure greatest degradation of pollutants within the smallest volume possible. One method of reducing lagoon size is to pre-treat influent to lower the mass of organic material entering the lagoon.

Since nuisance conditions are largely influenced by the biological communities working to degrade waste, the next generation of lagoons should be designed to promote the growth of specific communities rather than reduction of gross influent parameters such as BOD.

Cycles of effluent storage, biological activity, and organic matter accumulation—combined with the layering of lagoon biota—cannot be ignored when considering improvements to lagoon design and operation. The fact that these cycles are exacerbated in extreme latitudes may ultimately be the driving force determining the practicality of lagoons for treating agricultural wastes in such locations.

RESEARCH AND EDUCATION PRIORITIES

The following research and educational priorities should be considered to advance knowledge of lagoons and improve their performance.

Cycles of Lagoon Performance

This paper has emphasized the fact that in temperate climates, the biological communities in lagoons operate in daily and annual cycles. Time sequenced data of temperature, light intensity, dissolved oxygen concentration, and chemical concentrations taken at all levels in the lagoon in many climatic conditions is needed. This data will lead to development of models to predict lagoon environmental conditions and internal circulation for all regions.

Fundamental Biological and Chemical Processes

Microbial communities involved in wastewater treatment have long been viewed as "black boxes." A thorough knowledge of the structure and function of these complex communities and their interactions with each other and their environment is important for the design and optimization of treatment processes. Community observations in full-scale lagoons and physical models that adequately represent the complex natural setting of lagoons are needed. Greater understanding must be gained of those processes and microbial communities not found in simplistic mechanical treatment systems.

Molecular Tools for Identification of Biological Communities

Classical bacterial identification techniques, using bacterial enumeration and characterization, have not allowed scientists to conduct a detailed analysis of community structure as diverse as those found in lagoon environments. Classical techniques do not accurately reflect the actual bacterial community structure, but rather the selectivity of growth media for certain bacteria (Amann et al., 1995). Within the last 10 years, the advent of molecular techniques have led to significant advances in microbial ecology and community dynamics. Major taxa of previously unidentified organisms have been found in a wide variety of environments (Chandler et al., 1997; Ward et al., 1990). Of the various techniques used to estimate microbial community composition and diversity in complex habitats, the most useful is the determination of the sequences of 16S ribosomal RNA (rRNA) or its genes, rDNA (Ward et al., 1992). Although the analysis of cloned 16S rRNA genes of a mixed population of microorganisms offers phylogenetic characterization of the resident organisms, it does not provide a good estimate of their abundance. Two approaches for studying microbial communities and diversity, Denaturing Gradient Gel Electrophoresis (DGGE) and Terminal Restriction Fragment Length Polymorphism (T-RFLP), show promise for applications in lagoon environments.

Design Parameters for Specific Microbial Communities

With a greater understanding of the biological communities participating in manure degradation and the environmental conditions expected in lagoons, comes an increased ability to design lagoons to promote specific communities. Models should be developed to predict the interaction of communities within a layered system, so that design parameters such as hydraulic retention time, food to microorganism ratio, specific growth rate of organisms, feed placement, feed timing, and effluent withdrawal can be manipulated to achieve organic matter degradation without creating nuisance conditions.

Training and Reference Materials

The greatest treatment design in the world is only as good as the operator who maintains it. Training and reference materials are needed covering the basics of treatment theory, the cyclic nature of lagoon operation, liquid balance to maintain proper operating levels (operating within an actual water year—not an "average" year), efficient lagoon nutrient use, and maintaining structural integrity. Materials should be sensitive to the operator's need to work within the limitations of an agricultural production system.

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