CLOSURE OF EARTHEN MANURE STRUCTURES (INCLUDING BASINS, HOLDING PONDS AND LAGOONS)

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Abstract. This paper summarizes what is known scientifically about the closure of earthen manure structures without artificial liners, including lagoons, storage basins and runoff holding ponds, and identifies needs to be examined further to better under the dynamics of closing such structures in an environmentally safe manner. The information presented here should be useful as a guide for state regulatory agencies considering rules for closure and for academicians and consultants who work with livestock production facilities.
Keywords. Lagoons, manure storage, earthen storages, seepage, closure, groundwater contamination.

Introduction

When a livestock production unit ceases operation, proper procedures need to be undertaken to properly close earthen manure structures without artificial liners, including lagoons, storage basins and runoff holding ponds, in order to assure protection of surface and groundwater. There are three primary environmental risks associated with such earthen structures: nutrients and pathogens, which can be a concern for both surface and groundwater quality, and degradable organic matter, which is a concern for surface water due to runoff from structure overflow during the closure process or from land application of the contents.

Earthen manure structures, properly designed, installed and operated according to accepted engineering standards (such as those defined by USDA-NRCS *Agricultural Waste Management Field Handbook* and ASAE Standard EP393.2, "Manure Storage," and ANSI/ASAE EP403.2, "Design of Anaerobic Lagoons for Animal Waste Management," should pose little risk to water quality. A well maintained earthen structure should show:

❑ Limited erosion of sidewalls due to wave action;

❑ Lack of erosion in the vicinity of a manure inlet pipe;

❑ Lack of erosion near areas used for contents agitation and removal;

❑ Well maintained sod on berms and exterior sidewalls (weed and tree growth controlled);

❑ No signs of burrowing animals in or around the berms or sidewalls; and

❑ Lack of seepage around pipes through the sidewall and along the toe of the berm.

The addition of manure to an earthen structure further reduces seepage rates due to physical, chemical and biological processes that contribute to the clogging of soil pores. The NRCS *Animal Waste Management Field Handbook (1992)* acknowledges a reduction in the coefficient of permeability by a factor of at least 10. This suggests that for a properly designed and constructed facility, maintaining an intact structure and liner after abandonment should be an environmentally sound practice to protect against seepage. However this may or may not be considered environmentally sound for other reasons, e.g., if the structure is allowed to overflow.

Poorly designed or poorly constructed earthen liners, as well as badly eroded ones can allow significant movement of contaminants into the soil adjacent to or below the structure before the time of closure. Soil borings may be necessary to accurately assess the movement of nutrients below inadequate earthen structures at the time of closure and to determine the proper procedures necessary for closure.

This paper is a summary of a White Paper prepared for the National Center for Animal Waste National Center for Animal Waste. The purpose of the White Paper was to examine what is known scientifically about closing earthen manure structures without artificial liners (such as lagoons, storage basins, runoff holding ponds) and determine what needs to be examined further to increase our understanding of the dynamics of closing them in an environmentally safe manner. This summary will first provide the authors' general recommendations for closure and then review the methods available for removing the contents of the structure and discuss in more detail the options for closure or alternative uses of the site.

Closure Procedures

General Recommendations

Based on a review of available literature and the professional judgment of the authors, several fundamental principles should be applied to the abandonment of earthen manure structures without artificial liners that were reasonably well designed and constructed and properly maintained during their useful life.

The preparation of an earthen manure structure for closure involves three critical principles:

1) Protection during the closure process of the soil/organic matter interface layer that forms a relatively impermeable natural liner around the structure contents.

2) Removal of all liquids and pumpable slurry.

3) Land application of removed liquids and sludge at agronomic rates.

After liquids and sludge are removed and utilized in an environmentally sound manner, there are four generally acceptable options for completing the closure process. Producers should check with local and state regulatory agencies since the closure of earthen manure structures is sometimes governed by specific state or local regulations. In some states, the producer is required to complete a closure report. Generally acceptable options for closure of an earthen manure storage include the following options.

Option A: Permanent elimination of an earthen manure structure

Option B: Permanent conversion to a fresh water pond

Option C: Breaching of the berm

Option D: Managing earthen manure structures at temporarily depopulated operations

The procedures outlined here assume that the liner has been adequately protected from erosion and other threats to liner integrity. If these assumptions are not correct, soil borings are needed to determine if a more extensive cleanup is required. Regardless of the intended end use, all conveyances (pipes and ditches) used to convey manure to the basin should be removed and replaced with compacted soil. A more complete explanation of each of these principles is given later in this paper.

Solids Characteristics of Typical Earthen Lagoon

In a manure storage or basin, the contents are likely to be relatively uniform throughout, with solids content ranging from 2 to 10%. In an anaerobic lagoon, however, three different zones are likely to be found. These zones seldom have distinct boundaries and are difficult to determine.

1. Relatively inert solids accumulate near the manure inflow points. This material may be high in phosphorus, with a discernible interface between the solids and the sludge. Complete removal of these solids is difficult without damaging the liner. Therefore, maintaining liner integrity should be of even greater concern than removal of all solids. There is typically more solids buildup in lagoons receiving manure from poultry and dairy operations than from swine.

2. A thick sludge, high in nutrients, bacteria and organic matter, is normally located just above the solids zone. Pumps designed to handle high

solids content can remove this material. While much of the readily degradable organic matter in the sludge should be broken down, it is still biologically very active and a likely source of much of the anaerobic degradation of incoming manure occurring in a lagoon.

3. Above the sludge is a liquid layer that is low in solids and moderately rich in nutrients. It is easy to pump with conventional chopper-agitators or irrigation pumps. The liquid and most of the sludge can be removed by pumping while maintaining the integrity of the liner. The liquid can be irrigated onto cropland, but it may be necessary in some cases to move sludge using tanker wagons.

The settled solids and sludge layers of an anaerobic lagoon can contain a significant amount of phosphorus that has settled out over the years (Table 1). According to Barker (1996), organic nitrogen compounds tend to accumulate in the sludge at levels that are up to 13 times higher than in the liquid while phosphorus accumulates at rates that are up to 55 times higher. In addition, the sludge may also contain significant concentrations of heavy metals, salts and other trace elements. These factors dictate the need for laboratory analysis and for expert agronomic advice prior to land application. Sheffield (2000) found sludge volumes and total nutrients to be highly variable in a study of 30 single-cell swine lagoons in North Carolina. He concluded that volume and concentration could not be estimated accurately based on values from other lagoons. Likewise, the land area needed to apply the sludge at agronomic rates was highly variable.

Sludge sampling

Sheffield, et al. (2000) states that measuring and sampling sludge should be done from a boat. For safety reasons, at least three people should be present: two in the boat and one on the lagoon bank. The extra person on the boat assists with entering and exiting the boat, and the extra person(s) on shore may be needed as a rescuer should anything go awry. Flat-bottom boats are recommended over canoes or V-bottom boats. Everyone in the boat should wear appropriate flotation devices.

Sheffield, et al. (2000) recommends measuring the amount of sludge and solids in a lagoon by lowering a lightweight, rigid, 1.27 to 2.54 cm diameter (0.5 – 1 inch) wooden or capped aluminum pole slowly into the lagoon until the liquid seems to become denser and thicker. Record the water level on the pole and continue to push the pole down until you feel you have reached the bottom of the lagoon. Again, record the water level on the rod and remove it from the lagoon. The difference between the readings is the depth of the sludge and solids. Commercially available sludge samplers are useful for collecting samples but do not work well for estimating sludge volume because of the density of anaerobic lagoon sludge. The sludge layer in a lagoon is a mobile fluid that forms peaks and valleys within the lagoon. Sheffield, et al. (2000) recommends that at least 10 depth measurements be taken randomly. For a more detailed assessment of sludge volume, a formal grid should be established over the surface of the structure. The Environmental Protection Agency recommends at least four grids per cell with no grids larger than 930 cu m (10,000 sq ft). Plot depth measurements at grid points to develop a contour map of sludge deposits on the bottom of the storage to estimate the amount of sludge and solids beneath the liquid.

Sheffield, et al. (2000) also states that the best time to take a sludge sample is while measuring for volume of sludge in a lagoon. This allows samples to be collected from several points around the interior of the lagoon. Depending on density and nutrient concentration, the samples may differ by as much as 100 percent from point to point. To draw a sample, insert a 1.3 to 1.9 cm diameter (0.5 to 0.75 inch) PVC pipe into the lagoon sludge until the pipe reaches the bottom. Wearing plastic or latex gloves, cap the end of the pipe to create a vacuum and slowly withdraw it from the lagoon. This will capture a core or profile of lagoon effluent and sludge. Once the pipe outlet is over a clean container, slowly break the vacuum and allow it to drain. Place several samples in the container and mix thoroughly. Use a plastic, wide-mouth bottle and follow laboratory instructions when shipping samples for analysis.

Protecting the Integrity of the Existing Earthen Liner During Closure

No matter which closure method is chosen, maintaining an intact liner is likely less of a danger to the environment than attempting its removal. As much sludge and solids should be removed from the basin as can be accomplished without endangering the integrity of the liner. In the event of poor liner design, construction or management or where the liner has been damaged, nitrogen movement may be found in soil borings beneath the storage. In these cases, removal of several inches of the soil liner may be necessary. However, this should be the exception rather than the rule, and a knowledgeable consultant should determine the need for such measures after soil borings and inspection.

Removal of Liquids, Pumpable Sludge and Solids

Removing sludge and solids from earthen manure structures can be accomplished by several methods.

❑ Agitate and remove the combined contents of the structure and land-apply.

❑ Remove and land-apply liquids; agitate, remove and land-apply sludge.

❑ Remove and land-apply liquids; dredge and land-apply sludge.

❑ Agitate and remove the structure contents, concentrate and remove solids, and land-apply.

❑ Use a sludge dredge and land-apply without dewatering.

Agitate the Combined Contents of the Structure and Land-Apply

In this method, liquid and sludge are mixed with an agitator or a chopper-agitator impeller pump. High-volume pumps (11,500 to 19,000 liters per minute; 3,000 to 5,000 gallons per minute) specifically designed for agitation and loading provide for suspension of solids. However, agitation equipment is generally only effective in suspending solids within about 15 m (50 feet) of the agitator. Because agitation equipment can erode earthen liners near the agitator, it should be used cautiously. Direct the agitation flow away from the liner and keep the agitation unit at least 3 feet away from the soil surface. The mixed contents can be pumped through a large-bore sprinkler irrigation system onto nearby cropland. At many sites, the removed material should be soil-incorporated to minimize odor, nitrogen volatilization and runoff potential.

Remove and Land-Apply Liquids; Agitate, Remove and Land-Apply Sludge

The liquid portion of the earthen structure is dewatered by irrigation onto nearby cropland or forage-land. The remaining sludge is then agitated and pumped into a sludge applicator. The sludge can be spread onto cropland or forage land or soil-incorporated. This method may not work as well with dairy manure due to its fibrous nature, larger particle sizes and higher solids contents, compared to swine and poultry manure structures. After the liquid and most of the sludge is removed, depending on the condition of the liner, it may be necessary to remove any remaining solids with a small track-type dozer or farm tractor with a bucket.

Remove and Land-Apply Liquids, Dredge and Land-Apply Sludge

The earthen structure is dewatered by irrigation onto nearby cropland or forage land. Sludge is then removed with a dragline or sludge dredge. Note that the dragline must be used very cautiously to avoid damage to the organic liner. With more fibrous manure, it may be practical to establish a gently sloping bermed area beside the structure to receive the dredged sludge and allow liquids to drain back into the earthen structure to provide additional dewatering. This may not be feasible with swine or other non-fibrous sludge that does not stack well. After air-drying to produce a semisolid or solid material, the sludge is hauled and spread with solid manure equipment onto cropland or forage-land at agronomic rates. Soil-incorporation should be used where feasible to better retain and utilize the nutrients in the sludge.

When removing sludge, the pumper or dragline operator must pay close attention to protect the organic liner. Any damage may not be noticeable until the liquid level drops. If the soil liner is disturbed, stop the activity immediately and do not continue until operations are modified to prevent further damage. A damaged liner should be repaired with suitable soil material as soon as possible.

Agitate and Remove the Structure Contents, Concentrate and Remove Solids, and Land-apply

The entire contents of the manure structure is thoroughly agitated and removed. Solids are separated from the mixture of sludge and liquid and the liquid is land-applied. The solids are land-applied, composted or otherwise utilized.

Use a Sludge Dredge and Land-Apply without Dewatering

Pumping dredges are commonly used to remove solids from municipal and industrial wastewater lagoons and holding ponds. A pumping dredge is typically a floating barge with a variable-depth-pumping head to remove sludge from the bottom of the structure. Power units can either be located on the barge or may be hydraulically operated pumping heads with power units located on the berm.

A higher concentration of solids can be removed from a lagoon with the sludge dredge because sludge is removed without agitation or dilution, thus reducing transportation cost. With the assistance of guide cables, dredges work back and forth across a lagoon, working their way down the earthen structure, until the solids are removed. Since the dredges do not use aggressive agitation or cleaning nozzles, equipment manufacturers and operators claim that pumping dredges do not negatively impact the condition of earthen liners.

Pumping dredges are best suited for large structures or where large amounts of solids must be removed. Because of their size and weight, dredges may be placed into and removed from an earthen structure with a crane.

Sludge Reduction Alternatives

Chastain and Darby (2000) studied a thickening process for lowering the cost of removing sludge from a dairy lagoon. By settling sludge from mixtures of sludge and water (1.93 and 3.99% total solids) for seven hours and draining the supernatant back to the lagoon, the volume of sludge was reduced by an average of 60%.

Several companies offer various lagoon additives intended to reduce the volume of sludge in anaerobic lagoons. These products provide a mix of various microorganisms, enzymes, proteins or catalysts to stimulate the microbial degradation of accumulated sludge. The Animal and Poultry Waste Management Center at North Carolina State University has evaluated several of these products since 1997. To date, these studies have been unable to verify significant reductions in sludge volume. This may be due to differences in dosage of product, method of application or type of operation where the products were tested.

Anecdotal information from producers in the Midwest, however, continues to indicate that some of these products may be effective. Some producers have used baker's yeast effectively to suspend solids by spreading 120 gm/l of fresh baker's yeast mixed (1 lb/gal) of lukewarm water at a rate of one l per 1.84 sq m (1 gal/75 sq ft) of liquid surface with the storage agitated and pumped two weeks later. (Sheffield et al., 2000)

Estimated Cost of Liquid and Sludge Removal

The cost of closing an earthen manure structure is a concern for many confined feeding operations. In many cases, the operation is closing because of financial difficulties, and there are simply no funds remaining to properly close the manure structures. Some states have handled this issue at the time the storage is initially approved by requiring a bond to be posted to cover all or part of closure costs. According to the Environmental Review Commission of the North Carolina General Assembly (2000), Oklahoma, Iowa and Missouri already have legal mechanisms in place to ensure that owners have the funding available for lagoon closure and have legislation that holds producers responsible for closing facilities through one-time fees, annual fees and financial sureties (statement of assets, irrevocable letter of credit, cash or cashier's check).

In 2000, the North Carolina Department of Environment and Natural Resources (DENR) reported there were 1,142 inactive lagoons on 745 farms and that 39 were considered high risk. They assigned 93% of the inactive lagoons a medium risk (requiring further study) because of the uncertainty over the behavior of nutrients contained in inactive lagoons and limited data regarding groundwater levels and surface water contamination. The primary source of pollutants in inactive lagoons was assumed to be the sludge because of high N and P levels. Using NRCS standards for lagoon closure, DENR estimated the cost of closure at $105,000/hectare ($42,000/acre), or $30,000,000 to close all inactive lagoons in the state. Actual closure costs in North Carolina were between $1.32 and $8.47 per cu m ($5 and $32 per 1,000 gal) of waste removed, according to the Environmental Review Commission of the North Carolina General Assembly (2000). The estimated closure costs for a 3,785 cu m (1,000,000 gallons) lagoon would thus range from $5,000 to $32,000. This is high enough that producers cannot be expected to voluntarily close their inactive lagoons.

Lindemann et al. (1985) studied sludge removal from three dairy lagoons. A tractor-PTO propeller agitator, a two-stage portable solids handling and irrigation pump worked well to remove high-solids sludge from both dairy and poultry lagoons. The nutrient value of the sludge was sufficient to offset 30 to 50% of the cost of pumping.

Hiring a custom applicator is often a feasible method of managing sludge. The high cost of sludge removal equipment is prohibitive for most producers, especially due to the infrequency of sludge removal. Also, many lagoons can accumulate sludge for up to 10 years or more before their treatment ability declines. The cost of hiring a contractor is largely based on the amount of sludge to be removed. A 1999 survey of custom applicators in Eastern North Carolina (Sheffield et al., 2000) showed that prices ranged from 0.4 to 1.3 cents per liter of sludge (1.5 - 5.0 cents/gal) of sludge. The difference in cost depended on the size of lagoon to be pumped; lagoon accessibility; distance to available application sites and whether the sludge was to be irrigated, broadcast or injected.

Land Application of Liquid and Sludge at Agronomic Rates

Material removed from the bottom of the storage will have significant quantities of nutrients. Producers should obtain a nutrient analysis, estimate the proper application rate based on soil tests and crops to be grown on the application site, and monitor the actual application rate. The accumulation of phosphorus in the sludge commonly determines the minimum land requirement, based on agronomic needs of crops. For this reason, nutrient management plans should consider that all P added to the structure is available for land application eventually and not underestimate life cycle land area requirements.

Factors influencing land area required to apply sludge during closure are:

- ❑ Nutrient analysis of sludge;
- ❑ Nutrient analysis of supernatant;
- ❑ Crop to be grown;
- ❑ Soil type;
- ❑ Soil fertility level (phosphorus);
- ❑ Local/State regulations;
- ❑ Application method.

Land application rates should not exceed the annual crop nitrogen requirements (land grant university extension services or local NRCS offices can provide assistance in determining recommended land application rates). Application sites should be evaluated for their current soil phosphorus level and risk of runoff or erosion contaminating surface water. State regulations and best management practices must be followed in selecting suitable land application sites.

Specific Earthen Manure Storage Closure Procedures

Option A. Permanent Elimination of Earthen Storage Structure

Option B. Permanent Conversion to a Fresh Water Pond

Option C. Breaching the Berm

Option D. Managing Manure Storages at Temporarily Depopulated Operations

Incremental Closure Procedures

Incremental closure is a modification of Option A listed above. It has been used to close abandoned lagoons in the Southeastern U.S. Incremental closure is well suited for the permanent elimination of lagoons in the following situations.

❑ Large surface areas (greater than 2 acres) where agitation is difficult

❑ Earthen manure structures with narrow embankments that are unable to support tractors and agitators to suspend settled solids and sludge

❑ Earthen manure structures with degraded embankments or slopes

❑ Earthen manure structures with bottoms below groundwater table

❑ Large length to width ratios that are difficult to properly mix or access with agitator

❑ Soil or fill material unavailable locally to completely fill existing structure

❑ Earthen manure structures that will ultimately have their sidewalls removed and the facility filled in with soil or reshaped to match the existing contour

An earthen manure structure that is incrementally closed would generally undergo the following steps.

1. Agitation equipment is located at one end or corner of the structure. Sludge is agitated, removed from the structure and land applied.
2. Once the depth of settled/accumulated material is reduced to less than about 0.3 m (1 ft) by agitation and pumping or with a sludge dredge, bulldozers or other earth moving equipment slowly move the sidewalls by adding fill at a rate of approximately 3 to 4.5 m (10–15 ft) at a time toward the center of the structure.
3. As the embankment is pushed inward, the agitated sludge will be displaced by the fill and pushed toward the center of the structure, rather than being covered with soil.
4. Soil cores should be taken to monitor the process and ensure that the fill encloses a minimal amount of sludge. Borings, with a soil auger, should be made and the depth of sludge remaining in the structure after the previous movement of the lagoon embankment estimated. No chemical analysis is required. Rather, the soil cores serve as a quality control practice to ensure that the sludge is being moved toward the open portion of the lagoon, rather than being buried. Cores should be taken along the filled-in area to depths corresponding to the previous bottom elevation of the structure. Each core should represent approximately 70 sq m (750 sq ft) of area. A record should be kept of where the cores were taken as well as a measure of amount of sludge remaining.
5. Agitation equipment is moved across fill surface as the earthen structure is filled in. Agitation, solids removal, embankment movement and soil core samples continue until the structure is reduced to a size manageable by agitation equipment alone or until all contents are removed.

The goal of incremental closure is to remove the vast majority of sludge material while avoiding handling thick layers of sludge greater than 0.13 m (5 inches) and potentially damaging the liner. To minimize the sludge layer thickness while closing the unit:

❑ Agitate sludge and solid material periodically, as the structure is closed;

❑ Move embankment a shorter distance; or

❑ Place the bulldozer blade lower in the existing soil to push sludge material over from beneath.

Timing of Closure

The proper timing of earthen lagoon or manure storage structure closure continues to be debated. Should it be closed immediately upon cessation of operation or would it be better to wait 3 to 5 years? While environmental concerns remain after operation ceases, the level of risk tends to decrease over time if the structure is properly maintained. A number of advantages and disadvantages, both economically and environmentally, exist for either scenario. Allowing more time for closure gives more flexibility in applying the sludge. Applying at agronomic rates may be very difficult given the high concentration of nutrients in the sludge layer, and applying the sludge over a period of years instead of all at once may be more environmentally friendly. The structure must be maintained during this time of disuse just as it was during operation, including regular inspections, controlling burrowing animals, maintaining proper vegetation on berms, and pumping when necessary to maintain safe water levels. Continued maintenance, along with the potential increased cost for setting up equipment to pump sludge multiple times rather than all at once, may represent a significant cost to the operation.

Advantages of immediate closure include:

❑ Expense of maintaining berms and pumping lagoon ends quickly;

❑ Possibility of overtopping or leakage ends quickly;

❑ Closing it in one operation should minimize expense of pumping and hauling sludge.

Advantages of slower closure include:

❑ Pathogens existing in sludge are more likely to die or be reduced to insignificant levels;

❑ Nutrients in sludge can be applied at agronomic rates over a longer period of time;

❑ Nutrients in sludge can be applied at agronomic rates over a longer period of time.

Summary and Conclusions

A thorough review of the literature dealing with closure of animal manure lagoons and earthen manure storages shows quite varied results and indicates the need for a site-specific evaluation in order to accurately evaluate the potential environmental damage from closure. Still, there are several conclusions that can be reached.

The overall potential for environmental contamination should be taken into account when closing a structure. Application on land with crops that can utilize the nutrients without damage to ground or surface water must be available. It may be important to properly schedule the removal and land application of sludge over a period of several crop years to ensure this happens. If land is not available to apply the sludge, other means of utilization must be available.

A site-specific evaluation is important to ensure that the structure was properly sited, designed, constructed and operated. If it was not and if an investigation shows contamination of the site is ongoing, closure procedures should be completed as soon as possible.

There are a number of questions that remain after our literature search, specifically:

❑ What is the most versatile and suitable equipment to efficiently dewater/desludge lagoons in an environmentally safe fashion?

❑ Are there chemical/biological additives that can reduce/liquefy sludge effectively?

❑ How much reduction in the sludge accumulation rate can be expected due to a solid — liquid separation system in the manure stream ahead of an earthen structure?

❑ Can models be developed to more accurately estimate sludge buildup?

❑ What is the mineralization rate of nitrogen and other nutrients to be land applied from sludge and what is the salt content of sludge?

TABLE 1. Livestock Anaerobic Lagoon Sludge Characteristics

Species	**Swine active[a]**	**Swine inactive[b]**	**Dairy[a] complete mix, sludge and supernatant**	**Dairy[c]**	**Poultry layer[a]**
Units	mg/l (lbs/1,000 gal)	mgl (lbs/1,000 gal)	mg/l (lbs/1,000 gal)	mg/l (lbs/1,000 gal)	mg/l (lbs/1,000 gal)
Total Nitrogen					
Average	2,930 (24.4)	2,690 (22.4)	2,290 (19.1)	1,990 (16.6)	2,500 (20.8)
Std. Dev.	1,620 (13.5)	1,320 (11)	1,040 (8.7)	830 (6.9)	1,420 (11.8)
Total Phosphorus (P_2O_5)					
Average	6,310 (52.6)	1,550 (12.9)	5,020 (41.8)	1,070 (8.9)	9,260 (77.2)
Std. Dev.	4,120 (34.3)	940 (7.8)	3,940 (32.8)	540 (4.5)	4,790 (39.9)
Potassium (K_2O)					
Average	780 (6.5)	170 (1.4)	1,100 (9.2)	1,750 (14.6)	1,180 (9.8)
Std. Dev.	470 (3.9)	170 (1.4)	860 (7.2)	600 (5)	920 (7.7)
Copper					
Average	36 (0.3)	144 (1.2)	60 (0.5)	13 (0.11)	12 (0.1)
Std. Dev.	36 (0.3)	160 (1.3)	48 (0.4)	15 (0.12)	12 (0.1)
Zinc					
Average	96 (0.8)	140 (1.2)	84 (0.7)	19 (0.16)	130 (1.1)
Std. Dev.	72 (0.6)	72 (0.6)	48 (0.4)	11 (0.1)	120 (1)

[a]= Barker, J.C., J.P. Zublena, and C.R. Campbell. 1994. Livestock manure production and characterization in North Carolina. Agri-Waste Management Bulletin. Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, NC.

[b]= Sheffield, R. E. 2000. Sludge and Nutrient Assessment of Inactive Lagoons in North Carolina. Presented at the 2000 ASAE Annual International Meeting. ASAE Paper No. 004121. ASAE, 2950 Niles Rd., St. Joseph, MI 49085-9659 USA.

[c]= Mukhtar, S. 2000. Assessment of Nutrients and Sludge from Dairy lagoons in Texas. (Unpublished data)

Published sludge accumulation rates are highly variable, but estimates can be made using Table 2 if field measurements are not available.

TABLE 2. Rates of sludge/solids accumulation in lagoons (modified from USDA-NRCS, 1992)

		Sludge Accumulation 1/hd/yr (ft³/hd/yr)
Swine	Nursery	85 (3)
	Grow/Finish**	452 (16)
	Sows and litter	1,500 (53)
	Sows (gestation) and boars	395 (14)
Dairy	Lactating cows	10.755 (380)
	Dry cow	7,500 (265)
	Heifers	4,530 (160)
Beef	Feeder (high energy diet)	4,955 (175)
	Feeder (high forage diet)	5,660 (200)
Poultry	Layer	14 (0.5)
	Broiler	17 (0.6)
	Turkey	23 (0.8)

** Bicudo, et al. (1999) found a value of 203 l/hd/yr (7.2 cu ft/hd/yr).

The full text of the White Papers is available for $25 from Midwest Plan Service, http://www.mwpshq.org/