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Estimation of Sludge Accumulation in Lagoons

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Abstract. *The results of several studies of sludge accumulation in swine manure treatment lagoons have indicated that the sludge accumulation estimation method provided by ANSI/ASAE EP403.3 (ASAE Standards, 2004) is inadequate for modern swine facilities. This paper describes the development of a new sludge accumulation model based on basic treatment and mass balance principles that will allow the model to be implemented for all animal species in a variety of situations. Model parameters include the addition of total and volatile solids, organic bedding, excess feed wastage, and soil. Physical and biological treatment is described by settling characteristics, the volatile solids destruction rate, and the sludge storage period.*

Model predictions were compared with all available data and the values in the current standard. It was determined that the model agreed with the majority of the available data within the uncertainty in the model parameters.

In the course of the study, additional problems with the current standard were uncovered. The current standard includes two sludge accumulation rates for poultry lagoons - one for layers and the other for pullets. Statistical analysis of the original data indicated that such a distinction was not justified. The sludge accumulation rate for dairy lagoons in the current standard was also found to be in error. The contributions of organic bedding and soil tracked into animal housing facilities by cows were ignored. Furthermore, the current standard does not provide the practicing engineer a method to account for these contributions to lagoon sludge accumulation, or for the influence of primary manure treatment.

It was concluded that using constant sludge accumulation rates is not adequate for lagoon design for modern animal production facilities. The new model overcomes this problem by providing a simple, flexible method that allows the practicing engineer to implement site-specific data, and professional judgment.

Keywords. Lagoon, treatment, animal manure

Introduction

Quantification of sludge accumulation has been a concern almost as long as treatment lagoons have been used. Studies dating back to the mid 1970's have provided sludge accumulation data for dairy, swine, and poultry lagoons (Nordstedt, and Baldwin, 1975; Barth et al., 1978 as cited by Sweeten et al., 1980).

Engineers have used the term sludge in a variety of ways. In some of the initial studies, the entire settled layer in a lagoon or a settling basin was defined as sludge (e.g. Sweeten et al., 1980). By the early eighties, a more detailed view of sludge in a treatment lagoon began to emerge. Fulhage (1980) suggested that lagoon sludge consists of only the non-degradable volatile solids (VS) and the fixed solids that accumulate at the bottom of a treatment lagoon. His sludge accumulation estimate for swine lagoons included an estimate of the VS destruction rate and the fraction of the total solids added to the lagoon that would settle to the sludge layer. Smith (1980) presented a two-layer concept to describe sludge accumulation. The lower layer was called the sludge bed and included all recalcitrant VS and FS. An active layer called the sludge blanket covered the sludge bed. Five years later, Barth and Kroes (1985) presented a complex lagoon sludge accumulation model that included inert sludge composed of FS, non-degradable VS, and an active sludge layer.

Engineers continue to use the term sludge to describe solids from a primary settling basin, and fully or partially biologically degraded waste. Such mixed use of the term has led to a great deal of confusion.

Background

Barth and Kroes (1985) provided sludge accumulation data obtained from 16 treatment lagoons in South Carolina. These data were used as the sole source of information for sludge accumulation in the current ASABE Standard for design of anaerobic lagoons for animal waste treatment (ANSI/ASAE EP403.3, *ASAE Standards,* 2004). The sludge accumulation rates in the current standard are given in Table 1.

Table 1. Sludge accumulation (*ASAE Standards,* 2004)

Species	m^3 / kg TS Added
Swine	0.00303
Poultry	
Layer	0.00184
Pullet	0.00284
Dairy	0.00455

The ASABE Standard specifies that the sludge volume (SV) be estimated as:

$$SV = TAW \cdot TS \cdot FA \cdot DA. \quad (1)$$

Where,

TAW = the average live animal weight for the sludge accumulation period, kg_{LAW},

TS = total solids produced per day per 1000 kg_{LAW}, kg / day - 1000 kg_{LAW},

FA = fraction of TS that accumulates as sludge as given in Table 1, and

DA = days allowed for sludge accumulation.

The only other design guidance provided in the current standard (*ASAE Standards*, 2004) is that the sludge volume can be increased if bedding is allowed to enter the lagoon, and the SV may be decreased if primary treatment is provided by liquid-solid separation.

The sludge accumulation standard does not provide the user an objective method to modify sludge accumulation rates since the only variable in equation 1 that can be adjusted is the mass of solids entering the lagoon (TS). Primary treatment of animal manure by screening or settling will remove a significant amount of material that would contribute to sludge accumulation. However, the FA values given by the current standard (Table 1) would not be expected to be the same following primary treatment.

Bedding of freestalls was a common practice on dairy farms in the 1980's and remains a common practice today. Therefore, it seems reasonable to assume that the sludge accumulation value (FA) for dairy lagoons given in Table 1 includes a bedding contribution. The calculation method provided by the current standard does not allow an engineer to employ available data or professional judgment to modify sludge accumulation rates based on bedding practices or implementation of primary treatment.

Over the last eight years, several investigators have measured lagoon sludge depths, calculated sludge accumulation rates, and have compared their findings with the current standard. Bicudo et al. (1999), Hamilton (2002), Morton et al. (2003) and Tyson et al. (2002) measured sludge accumulation rates in swine lagoons treating manure from all phases of production. The combined data from these four studies represents information from 58 different lagoons. The mean sludge accumulation rates in these studies ranged from 25% to 79% of the value predicted by the current standard.

Very little data is available concerning sludge accumulation in dairy and poultry lagoons. Over the last five years, the only study that included sludge depth measurements for dairy lagoons was by Mukhtar et al. (2004). The sludge depth averaged 0.46 m, but was as high at 1.7 m. The influence of manure handling methods, bedding practices, and use of primary treatment affected the amount of sludge accumulated. Sludge volume was not measured in this study, and as a result, comparisons between observations and the current standard could not be made. The only other sludge accumulation data for dairy or poultry lagoons preceded the development of the current standard (Barth et al., 1978; Barth and Kroes, 1985; Nordsted and Baldwin, 1975).

Objectives

The sludge accumulation estimation method provided by ANSI/ASAE EP403.3 (*ASAE Standards*, 2004) is inadequate for modern swine, dairy, and poultry facilities. The objectives of this paper are to (1) describe the development of a new model to estimate lagoon sludge accumulation, (2) provide a summary of lagoon sludge accumulation data, and (3) compare model results with the available data and the current standard.

Model Description

Over the last five years, a few authors have suggested alternative methods for estimation of lagoon sludge accumulation (e.g. Bicudo et al., 1999; Hamilton, 2004). However, all of these improvements were based solely on observations of sludge accumulation in swine lagoons. Their methods did not permit extension to other animal species.

The goal of the present model is to begin with basic treatment and mass balance principles that will allow the model to be implemented in a variety of situations.

Sludge is defined as the non-degradable volatile solids and the fixed solids (or ash) that accumulates at the bottom of a treatment lagoon over a specified time period. The space occupied by the sludge is not considered to be part of the active treatment volume since it is biologically inert.

The active treatment volume of the lagoon is the volume composed of the active settled solids and the supernatant. Active settled solids are composed of the VS that have recently settled to the bottom and the older VS that are in various stages on decomposition.

The volume of the sludge layer and the active treatment volume are continuously changing, and the physical boundary cannot be finely distinguished. However, the concepts that underlie the estimation of sludge accumulation are given as well defined zones in Figure 1.

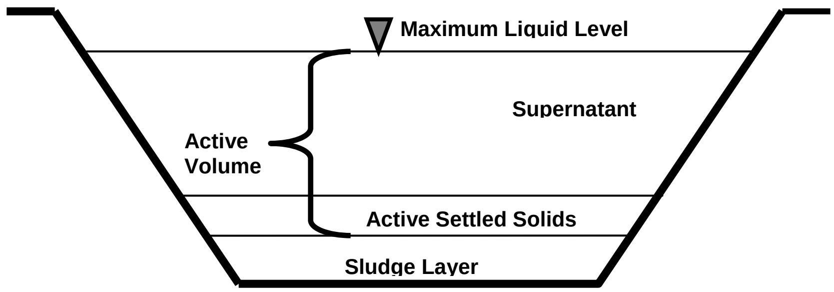

Figure 1. Conceptual components of a treatment lagoon used to estimate sludge accumulation.

Using the concepts described in Figure 1, a simplified expression of a mass balance on the sludge layer over a defined period is: M_{SL} = Mass of non-degradable, settleable VS + Mass of settleable FS. Where, M_{SL} is the mass of sludge accumulated during the defined sludge storage period, and the mass of FS is the difference between the mass of TS and VS.

The mass of sludge that accumulates over a specified time, T, was written in terms of settling and VS destruction parameters as:

$$M_{SL} = [(1-F_{VSD})\ S_{VS}\ MVS + S_{TS}\ MTS - S_{VS}\ MVS + MFS_{SOIL}]\ T. \quad (2)$$

Where,

M_{SL} = mass of sludge,

F_{VSD} = fraction of VS destroyed over the specified time period,

S_{VS} = fraction of VS that settles to the sludge layer,

MVS = mass of VS loaded per day = (VS /TS) · MTS,

S_{TS} = fraction of TS that settles to the sludge layer,

MTS = mass of TS loaded per day (manure solids + wasted feed + organic bedding),

MFS_{SOIL} = mass of soil or sand bedding added per day,

T = (δ · θ) = sludge storage period in days,

δ = number of days the lagoon is loaded per year, and

θ = number of years for sludge storage.

The volume occupied by the inert sludge layer depends on the concentration of TS. The volume of the sludge layer is simply:

$$V_{SL} = M_{SL} / [TS_{SL}]. \quad (3)$$

Where,

$[TS_{SL}]$ = the concentration of the TS in the sludge layer, g/L or kg/m^3, and

V_{SL} = volume of the sludge layer in L or m^3.

Volatile Solids Destruction in Animal Waste Lagoons - F_{VSD}

Barth and Kroes (1985) provided tabulated data concerning sludge accumulation for six swine lagoons, six poultry lagoons, and four dairy lagoons. Sludge had not been removed from any of the lagoons included in their study. Therefore, the total time that sludge had been allowed to accumulate was known. The fraction of VS destroyed, F_{VSD}, was calculated from the data and has been plotted with respect to sludge storage period in Figure 2.

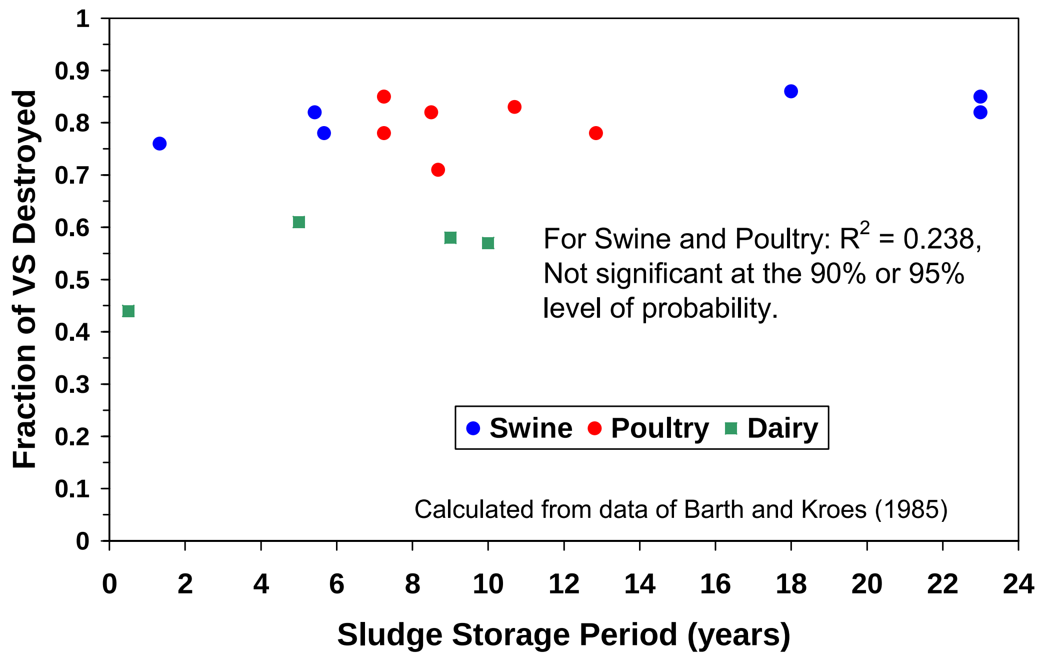

Figure 2. Destruction of volatile solids observed for treatment of animal manure in lagoons.

It was hypothesized that the amount of VS destroyed in swine and poultry lagoons would correlate well with respect to the sludge storage period, but statistical analysis indicated that this was false. Linear regression analysis of the F_{VSD} values indicated that VS destruction in swine and poultry lagoons were not significantly different. An F-test on the pooled regression (swine and poultry) of F_{VSD} with respect to the sludge storage period was not significant at the 90% or 95% level of probability (Steel and Torrie, 1980).

Destruction of VS in dairy lagoons was lower than for the swine and poultry lagoons. One of the dairy lagoons was only in operation for 0.5 years at the time of the study and the value of F_{VSD} (0.44) was lower than the three older lagoons. This lagoon was eliminated from subsequent analyses since it had been functioning for such a short time.

A one-way analysis of variance, with unequal replication, was performed on the F_{VSD} data. Animal species defined the treatments, and the pooled variance (S_P^2) was based on 12 error degrees of freedom.

Comparisons of treatment means, using a least significant difference test at the 95% probability level, indicated that the VS destruction was not significantly different for swine and poultry lagoons. This was not surprising since swine and poultry are fed a ground corn and soybean diet, and both are monogastric animals. The mean value of F_{VSD} for the three dairy lagoons was 27% lower than for the lagoons used to treat manure from monogastric animals. The treatment means as well as the pooled standard deviation (S_P) are given in Table 2.

The maximum VS destruction rates for mesophilic anaerobic digestion, provided by Hill (1991), are compared with the VS destruction rates for lagoons in Table 2. The long solids retention time provided by a treatment lagoon provides substantially higher VS destruction than a well-mixed or plug-flow digester.

Table 2. Comparison of mean values of VS degradation (F_{VSD}) observed for treatment by lagoon, and anaerobic digestion.

Species	Treatment Lagoon[1] F_{VSD} (mean ± S_P)	Mesophilic Anaerobic Digestion[2] F_{VSD}
Swine (n = 6)	0.82 a	
Poultry (n = 6)	0.80 a	
Mean for Swine and Poultry	0.81 ± 0.042	0.63
Dairy (n = 3)	0.59 ± 0.042	0.23

[1] Mean values of data shown in Figure 1; numbers with the same letter were not significantly different; S_P = 0.042; LSD to compare dairy with swine and poultry = 0.064.

[2] Theoretical maximum VS destruction values for well-mixed and plug flow digesters (Hill, 1991).

Settling Parameters - S_{TS} and S_{VS}

The settling parameters, S_{TS} and S_{VS}, describe the primary treatment that will occur in a lagoon. The fraction of VS that settles, but will not degrade within the sludge storage period, is a key contributor to the sludge layer. If it was possible to completely degrade the volatile matter in the settled material (i.e. F_{VSD} = 1.0) the sludge layer would be entirely composed of settleable fixed solids.

Settling data from several studies were reviewed to develop recommended values of S_{TS} and S_{VS} for swine and dairy lagoons. The recommended averages and ranges are given in Table 3. The coefficient of variation in the values of S_{TS} and S_{VS} was on the order of ± 20%.

Table 3. Range and average values for settled mass fractions for TS and VS for swine and dairy manure.

Species	Fraction TS settled, S_{TS} Average (range)	Fraction VS Settled, S_{VS} Average (range)
Swine [1]	0.47 (0.38 to 0.56)	0.49 (0.40 to 0.58)
Dairy [2]	0.51 (0.41 to 0.61)	0.56 (0.47 to 0.64)

[1] Data range from Fischer et al. (1975), Baker (2002), and Chastain and Vanotti (2003)

[2] Data range from Chastain et al. (1999), Baker (2002), Chastain et al. (2001), Converse and Karthikeyan (2004).

No data were found in the literature that provided TS and VS removal efficiencies for poultry manure. Sobel (1966) measured gravity settling rates, and settled volume fractions for dairy and poultry manure, but did not provide any information on VS settling. The fraction of TS that settled for poultry manure was similar to that found in later studies for swine manure. Therefore, if no other data are available, estimate sludge accumulation in poultry lagoons using settling parameters for swine manure.

Solids Content of the Sludge Layer - [TS_{SL}]

Estimation of the volume occupied by the sludge layer necessitates an estimate of the total solids content on a volume basis. However, the TS concentration can vary greatly depending on lagoon depth, the amount of time the settled material has been allowed to thicken by compression, and average particle size.

Published values of [TS_{SL}] were obtained from the literature for 19 swine lagoons, 5 dairy lagoons, and 5 poultry lagoons. The data ranges, means, standard deviations (by treatment and pooled), and the corresponding 95% confidence intervals are given in Table 4.

Table 4. Summary of data on the total solids content in the sludge layer of animal manure treatment lagoons.

	[TS_{SL}] (g/L)		
Species	Data Range	Mean ± S	95% C.I.
Swine (n = 19) [1]	82.0 to 204	106 ± 31.3	(90.9, 121)
Dairy (n = 5) [2]	97.5 to 154	121 ± 27.1	(78.0, 164)
Poultry (n = 5) [3]	98.9 to 215	154 ± 44.8	(98.4, 210)
	Grand Mean	127 ± 33.3	(114, 140)

[1] Smith (1980), Fulhage (1980), Barth and Kroes (1985), Bicudo et al. (1999)

[2] Norstedt and Baldwin (1975), Barth and Kroes (1985)

[3] Barth and Kroes (1985)

It was hypothesized that the magnitude of [TS_{SL}] would have some definable dependence on animal species. However, statistical analysis of the available data did not support this hypothesis since the 95% confidence intervals overlapped in all cases.

If no other relevant data is available to the practitioner, the recommended value of [TS_{SL}] for estimation of sludge volume for an animal manure treatment lagoon is 127 ± 33.3 g/L (kg/m^3).

Estimates of TS and VS Production

Estimates of the TS and VS produced by swine, dairy, and poultry animals are given in Table 5 from a variety of sources. These values do not include estimates of feed wastage greater than 5%, bedding, or soil that may be added to a lagoon. The designer of a treatment lagoon should use the most representative information available or rely on the revised ASABE manure production standard (ASAE D384.2 MAR2005, *ASAE Standards*, 2005).

The loading of a treatment lagoon will depend on the total live animal weight contained in all of the facilities on the farm. In many cases, such as a farrow-to-feeder swine farm, the total live animal weight will include all breeding stock, growing animals of various weights, and replacement animals. Average live animal weights per production unit, PU, were included in Table 5 to facilitate estimation of the amount of TS and VS loaded per year. The production unit, or the animal type that is used to describe farm size, will depend on farm type and was defined as a sow, pig, hog, layer, cow, or steer. For example, a 1000-sow farrow-to-feeder farm will have an average live animal weight at any time of 237,000 kg_{LAW} (1000 x 237 kg_{LAW} / sow).

Table 5. Estimates of manure solids production by swine, poultry, dairy, and beef animals (includes feed wastage up to 5%).

Species	g TS_M / kg_{LAW}-day [1]	VS/TS	kg_{LAW} / PU [2]	Reference
SWINE	11 ± 6.3	0.77		*ASAE Standards* (1998)
Growing &Finishing	6.34	0.85		NRCS (1992)
Replacement gilt	3.28	0.89		"
Gestating sow	2.50	0.85		"
Lactating sow	6.0	0.90		"
Boar	1.9	0.89		"
Farm Type				
Farrow-to-Wean	5.9	0.77	196 / sow [3]	Chastain et al. (1999)
Nursery	11.0	"	14 / pig [4]	"
Farrow-to-Feeder	6.7	"	237 / sow [3]	"
Feeder-to-Finish	11.0	"	64 / hog [4]	"
Farrow-to-Finish	9.3	"	643 / sow [3]	"
DAIRY	12 ± 2.7	0.83		*ASAE Standards* (1998)
Lactating cow (low production)	10	0.85	612 / cow [5]	NRCS (1992)
Lactating cow (high production)	14.4	0.83	"	Chastain and Camberato (2004)
Dry cow	9.5	0.85		NRCS (1992)
Heifer	9.14	0.85		"
POULTRY				
Layer	16 ± 4.3	0.75	1.81 / hen [4]	*ASAE Standards* (1998)
Layer	15.1	0.72		NRCS (1992)
Pullet	11.4	0.85		"

[1] kg_{LAW} = kg of average live animal weight.

[2] PU = production unit. The production unit is a sow, pig, hog, layer, cow, or steer (Chastain et al., 1999)

[3] Includes weight contribution of all animals (piglets, breeding stock, etc.)

[4] Average live animal weight = [entry weight + exit weight] / 2

[5] Average weight shown is for Holstein cows. Use 408 kg for Jerseys.

Manure excreted by animals is not the only source of solids that can be loaded into a treatment lagoon. The most common are wasted feed, bedding, feathers and soil tracked into the building by animals.

Wasted Feed

Wasted feed can make a significant contribution to the organic load of a lagoon and will add volume to the sludge layer. If feeders are operating properly on swine and poultry farms the amount of feed wasted will be noticeable, but will be 5% or less. On dairy farms, the amount of feed wasted can be substantial if feeding fences or feed bunks are improperly designed. Anticipated feed wastage greater than 5% should be accounted for in the estimation of the daily solids production.

The NRCS (1992) recommends increasing the manure solids production by 4% for every 1% of feed wastage over 5%. The multipliers given in Table 6 were based on the NRCS recommendation.

Table 6. Wasted feed factors (based on NRCS, 1992).

Anticipated Feed Wastage	f_{FW}
5% or less	1
6%	1.04
8%	1.12
10%	1.20

Bedding

No bedding is needed on modern swine and poultry farms with liquid manure handling systems. However, use of organic and sand bedding is common in freestall dairy barns.

The actual amount of organic bedding used will vary greatly from farm-to-farm. Therefore, an engineer should obtain site-specific data if possible. If no other data are available, assume that bedding adds 3 g of TS per kg_{LAW} per day (NRCS, 1992). This estimate assumes that adding organic bedding will not alter the settling characteristics, and the VS/TS ratio will remain about the same. The results of a case study of treating heavily bedded flushed dairy manure support these assumptions (Chastain et al., 2001).

Sand is a popular bedding material for freestalls in dairy barns. Sand use rates vary from 20 to 40 g per kg_{LAW} per day (Bickert et al., 2000).

With regard to lagoon sludge accumulation, sand bedding is treated as soil (MFS_{SOIL} in equation 2), because it is composed entirely of settleable fixed solids. All sand that is kicked out of the freestalls will contribute to sludge mass. As a result, primary treatment to remove sand should be provided prior to a lagoon on all dairy farms that use sand bedding.

Calculation of MTS

The mass of total solids generated on an animal farm includes contributions from manure, wasted feed, and organic bedding. Use the following expression to estimate the value of MTS to be used in equation 2:

$$MTS = f_{FW}\, TS_M + M_{OB}. \qquad (4)$$

Where,

f_{FW} = wasted feed factor (Table 6),

TS_M = mass of TS from manure (gTS_M / kg_{LAW}-day,), and

M_{OB} = mass of organic bedding added to the manure (g / kg_{LAW}-day).

Soil

On many dairy farms, the milking herd is allowed access to paddocks or pastures. Consequently, soil will be brought into the freestall barn on hooves and animal bodies and much of the soil will be added to the lagoon. All of the soil that enters the lagoon will settle to the sludge layer. Include 1.5 g of soil per kg_{LAW} per day to the settleable fixed solids (MFS_{SOIL} in equation 2) if cows are allowed access to outside areas on a daily basis.

Inclusion of the Affects of Primary Treatment

Primary treatment of liquid animal manure by mechanical screening or sedimentation will reduce the amount of solids that will settle to the sludge layer. Therefore, the affects of providing primary treatment prior to the lagoon can be included in the sludge accumulation model by making appropriate reductions in the following parameters MTS, MVS, S_{TS}, S_{VS}, and MFS_{SOIL}.

Specific information concerning the impact of particular methods of primary treatment is beyond the scope of this paper.

Summary of Parameters for High, Average, and Low Sludge Accumulation

Estimation of sludge mass (equation 2) and volume (equation 3) depends on parameters that have a large amount of variation, or uncertainty. As a result, one must be mindful of the uncertainty introduced into calculated estimates of sludge volume when comparisons are made with data or other estimation methods.

The parameters that define low, average, and high sludge accumulation rates for swine, poultry, and dairy lagoons are summarized in Tables 7 and 8. These values will provide sludge accumulation estimates that correspond to variations of one standard deviation about the mean input parameters. Low sludge accumulation rates will occur when the upper limit of VS degradability (F_{VSD}) and [TS_{SL}] are combined with the lower limits for settling. The other extreme, high accumulation, will occur when the converse is true.

Table 7. Model parameters for low, average, and high sludge accumulation rates for swine and poultry manure

	Low Accumulation	**Average Accumulation**	High Accumulation
F_{VSD} =	0.852	**0.81**	0.768
S_{TS} =	0.38	**0.47**	0.56
S_{VS} =	0.40	**0.49**	0.58
[TS_{SL}] =	160	**127 g/L**	93.7

Table 8. Model parameters for low, average, and high sludge accumulation rates for dairy manure

	Low Accumulation	**Average Accumulation**	High Accumulation
F_{VSD} =	0.632	**0.59**	0.548
S_{TS} =	0.41	**0.51**	0.61
S_{VS} =	0.47	**0.56**	0.64
[TS_{SL}] =	160	**127 g/L**	93.7

Summary of the Available Sludge Accumulation Data

Available data concerning accumulation of sludge in animal manure treatment lagoons are summarized in Table 9. Seven studies provided observations for swine lagoons, but only two or three provided values for poultry and dairy lagoons. In all cases, researchers measured sludge levels in multiple locations in the lagoon. Lagoon sludge accumulation rates were calculated from data and were typically expressed in terms of volume per mass of live animal weight per year (m^3 / kg_{LAW}-yr), and volume of sludge per mass of TS added during the sludge storage period (m^3/kg TS Added). A few researchers only reported sludge accumulation values using one set of units. In most cases, the daily solids production used by the researcher was given. If the solids production was not given an estimate was made using Table 5 or the reference indicated in Table 9.

Table 9. Summary of available data concerning lagoon sludge accumulation in animal waste treatment lagoons.

Species	Solids Loading	Sludge Accumulation, mean ± S	
	g TS / kg_{LAW} - day	m^3 / kg_{LAW} -yr	m^3 / kg TS Added
SWINE			
Barth et al. (1978)	6.61 [1]	0.00492 *	0.00204
Barth and Kroes (1985) n = 6	6.61 [1]	0.00783* ± 0.00247	0.00303* ± 0.00061
Fulhage (1980)	4.93*	0.0022*	0.00120*
Bicudo et al. (1999) n = 15	8.1 [2]	0.003* ± 0.00054*	0.00101 ± 0.00018
Hamilton (2002) n = 7 [3]	5.9	0.00353 ± 0.00078	0.00164* ± 0.00036
Tyson et al. (2002) n = 4	6.34	0.00343* ± 0.00092	0.00130* ± 0.00026
Morton et al. (2003) n = 37			
Sows (Farrow-to-wean) n = 7	2 (5.9)[4]	0.0020* ± 0.0015*	0.0034* (0.0009)
Finishing and Nursery Farms	6.5 [5]	0.0045* ± 0.0015*	0.0019*
Weighted Mean	5.65 (6.38)		0.0024* ± 0.0009* (0.0017 ± 0.0006)
POULTRY			
Barth et al. (1978)	13.3 [1]	0.00889*	0.00187
Barth and Kroes (1985) n = 6	13.3 [1]	0.01053 ± 0.00296	0.00217* ± 0.00061
DAIRY			
Nordsted and Baldwin (1975)	9.4 [1]	0.0094	0.00274* [5]
Barth et al. (1978)	9.4 [1]	0.01203*	0.00351
Barth and Kroes (1985) n = 3	9.4 [1]	0.0156* ± 0.0025	0.00455* ± 0.00061

* Value given in the reference.

[1] Value from Barth (1985) and includes 5% feed wastage.

[2] Weighted average solids production for six farrow-to-feeder, two farrow-to-wean, four farrow-to-finish, and three finishing farms (Table 5).

[3] Calculated from tabulated data provided in reference and shown in Figure 3. Solids production estimate of 5.9 gTS / kg_{LAW}-day is for a farrow-to-feeder farm given in Table 5

[4] Solids production was calculated by authors based on diet for sows. The value in parentheses was taken from Chastain et al. (1999) as shown in Table 5 and includes solids production from the litter, boars, and replacement animals.

[5] Solids production was calculated by authors based on diet for growing and finishing animals. Values shown were back calculated from the mean values of m^3 / kg_{LAW} -yr and m^3 / kg TS Added.

Only two studies (Bicudo et al., 1999; Morton et al.,2003) provided values for the standard deviation (S) about the reported mean. If the standard deviation was not provided in the study, the author calculated it where possible. The standard deviation was used as the estimate of uncertainty about the reported averages.

The data used for ANSI/ASAE EP403.3 (*ASAE Standards,* 2004), and given in Table 1, was originally published by Barth and Kroes (1985). The original publication did not provide any statistical analysis.

The data of Barth and Kroes (1985) was organized into a complete randomized block with unequal replications. The treatments were defined by lagoon type. Treatment means were compared using the least significant difference computed as: LSD (12, 0.05) = 2.179 S_P $[(1/n_1 + 1/n_2)]^{0.5}$ (Steel and Torrie, 1980). The current standard has two values for poultry lagoons, one value for layers and another for pullets. However, statistical analysis of the data does not warrant such a distinction since the means were not significantly different The pooled standard deviation for this block of data is shown with the mean values for swine, dairy, and poultry in Table 9.

Bicudo et al. (1999) provided sludge accumulation data for six farrow-to-feeder farms, two farrow-to-wean farms, four farrow-to-finish farms, and three feeder-to-finish farms. The data from the 15 lagoons was pooled into a single linear regression equation. The result was the following equation (R^2 = 0.70): AS = 0.003 θ (Bicudo et al., 1999). Where, AS is the accumulated sludge (m^3/kg_{LAW}) and θ is the sludge accumulation period (years). An uncertainty interval about the regression line that contained two thirds of the observations was shown in the figure provided in the publication. This interval was estimated from the figure and is given in Table 9. Bicudo et al. (1999) did not provide an estimate of sludge accumulation in terms of m^3 / kg TS Added. The value and interval shown (m^3 / kg TS Added) in Table 9 was estimated based on a weighted mean solids production rate of 8.1 gTS / kg_{LAW}-day and the uncertainty interval about 0.003 m^3 / kg_{LAW} -yr.

Hamilton (2002) measured sludge accumulation with respect to time in two swine lagoons in Oklahoma. It was estimated that the uncertainty in sludge depth measurements was ± 0.03 m. Plotting Hamilton's sludge accumulation data with respect to sludge depth (Figure 3) indicated that at sludge depths ranging from 0.07 to 0.24 m the error in measurements ranged from 12% to 42%. Furthermore, sludge volume measurements at the lower sludge depths appeared to be lower than measurements for which the uncertainty in sludge depth ranged from 3% to 8%. For this reason, the mean and standard deviation reported in Table 9 based on Hamilton's data was based on the seven sludge accumulation values that corresponded to sludge depths of 0.38 to 1.02 m.

Morton et al. (2003) provided the largest available study of swine lagoon sludge accumulation. Their data set included measurements from 7 sow farms (farrow-to-wean), 15 nursery farms, and 15 finishing farms (feeder-to-finish). One of the unique features of this study was that the solids production on these farms was calculated from the composition of the animal diets as provided by the swine producer. The daily solids production values were not given in the publication. The solids production values shown in Table 9 were computed from the mean sludge accumulation rates given in terms of m^3 / kg TS Added and m^3 / kg_{LAW} -yr. The daily solids production of 6.5 gTS / kg_{LAW}-day for the nursery and finishing farms compares favorably with values for growing and finishing animals given in Table 5. However, the solids production for the sow farms appears to be too low. It is believed that the TS calculation does not adequately reflect the different phases of feeding used for sows, and it excludes the solids production of the fast growing piglets and manure from other swine. Another estimate for daily TS production of 5.9 g TS / kg_{LAW}-day is shown in parenthesis. This value was taken from Table 5 and includes solids contribution from lactating sows, an average litter size of 10 piglets, breeding and gestating sows, boars, and replacement gilts.

Comparison of the sludge volumes per kg TS Added indicate that the valve of 0.0034 calculated based on about 2 kg TS /kg_{LAW}-day was 79% higher than the value observed for the grow/finish swine (0.0019 m^3 / kg TS Added). Assuming the solids production was 5.9 g TS / kg_{LAW}-day the sludge volumes normalized with respect to TS added would be reduced to 0.0009 m^3 / kg TS Added. Furthermore, the weighted overall mean would be 0.0017 ± 0.0006 m^3 / kg TS Added. The estimate of the uncertainty was calculated using the standard deviation of the sludge volume expressed as m^3 / kg_{LAW} -yr and the weighted mean value for solids production (6.38 g TS / kg_{LAW}-day).

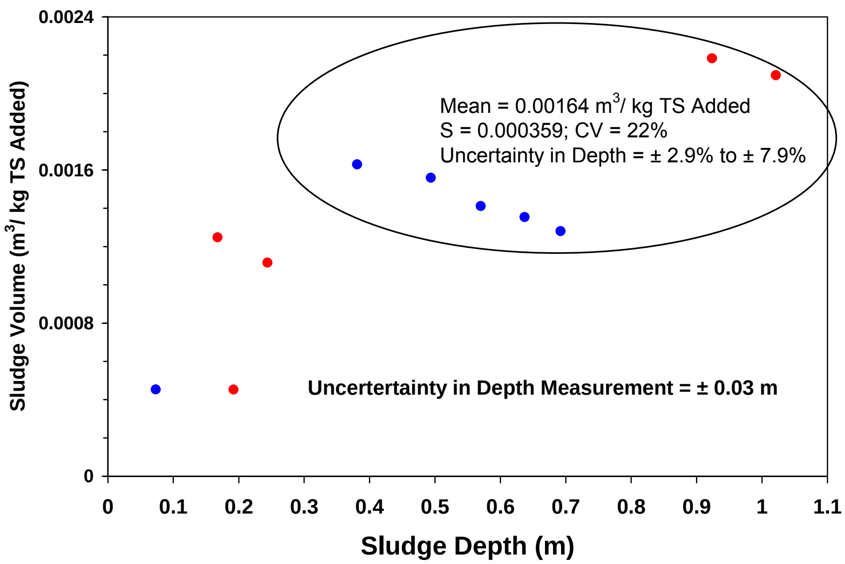

Figure 3. Analysis of sludge accumulation data provided by Hamilton (2002). Data taken at sludge depths below 0.38 m were not included due to the large uncertainty in the measurements.

Comparison of the Model with Data

Comparison of sludge volume observations from different studies, and a prediction model must include an estimate of the uncertainty. Without a reasonable uncertainty estimate, it is impossible to make a valid comparison. The estimate of the uncertainty for the data are the standard deviations given with the means in Table 9. The influence of uncertainty in the model predictions was defined by the range of model parameters given in Tables 7 and 8. Therefore, the model was used to provide sludge volumes for high, average, and low sludge accumulation rates.

Comparisons for Swine Lagoons

The majority of the available sludge volume data is for lagoons treating swine manure. In most cases, the researchers initially expressed the sludge volume in terms of volume per mass of live animal weight per year (m^3 / kg_{LAW}-yr). Normalization of the sludge volume with respect to the mass of TS added to the lagoon was typically based on an estimate of the daily production of manure solids (m^3 / kg TS Added). Sludge volume data, estimates using the new model, and values from the current standard are compared for swine lagoons in Figures 4 and 5.

Results shown in the figures indicate good agreement between the model and all data except for the data of Barth and Kroes (1985) which was the basis of ANSI/ASAE EP403.3 (*ASAE Standards*. 2004). In addition, all of the means lie within the uncertainty of the model calculations defined by the high and low sludge accumulation rates.

The predictions using the new model, as well as the majority of the sludge accumulation data, fell well below the data of Barth and Kroes (1985) and the current standard. The oldest data, provided by Barth et al. (1978) and Fulhage (1980) also agreed with the new model within the uncertainty in model inputs.

The exact reason for the discrepancy between the data of Barth and Kroes (1985) and all other studies is unknown. However, it may be that the total solids estimate for these lagoons was too low. Large amounts of wasted feed and addition of soil was not uncommon in many older swine feeding facilities. Underestimation of the mass of TS loaded would yield a high sludge volume expressed as m^3 / kg TS Added.

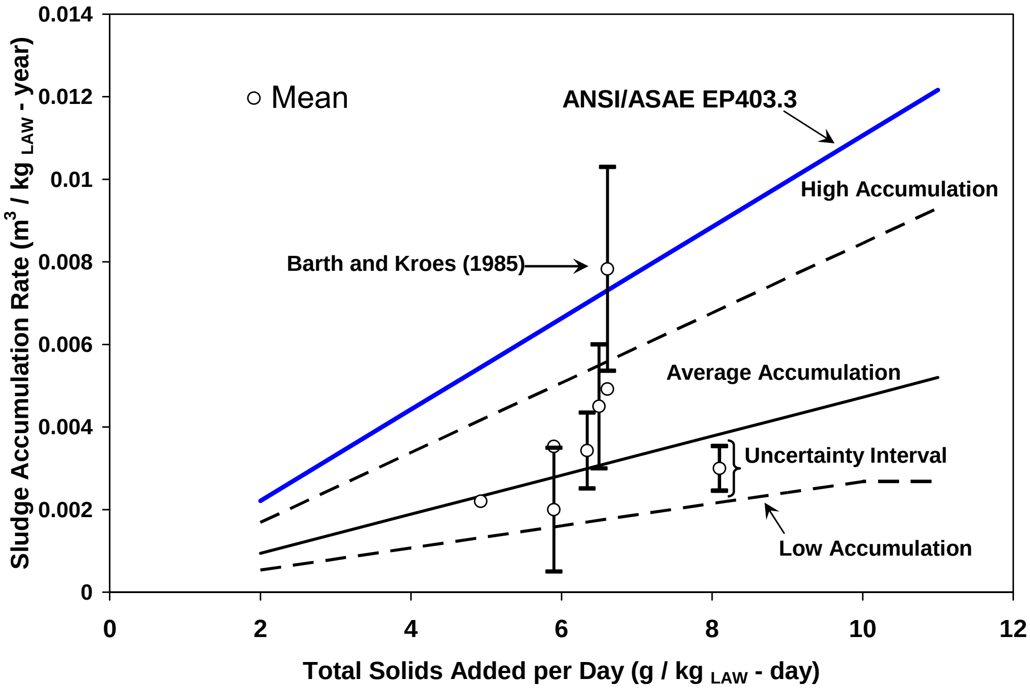

Figure 4. Comparison of model estimates and data for sludge volume in swine treatment lagoons with estimates predicted using ANSI/ASAE EP403.3 (*ASAE Standards*. 2004).

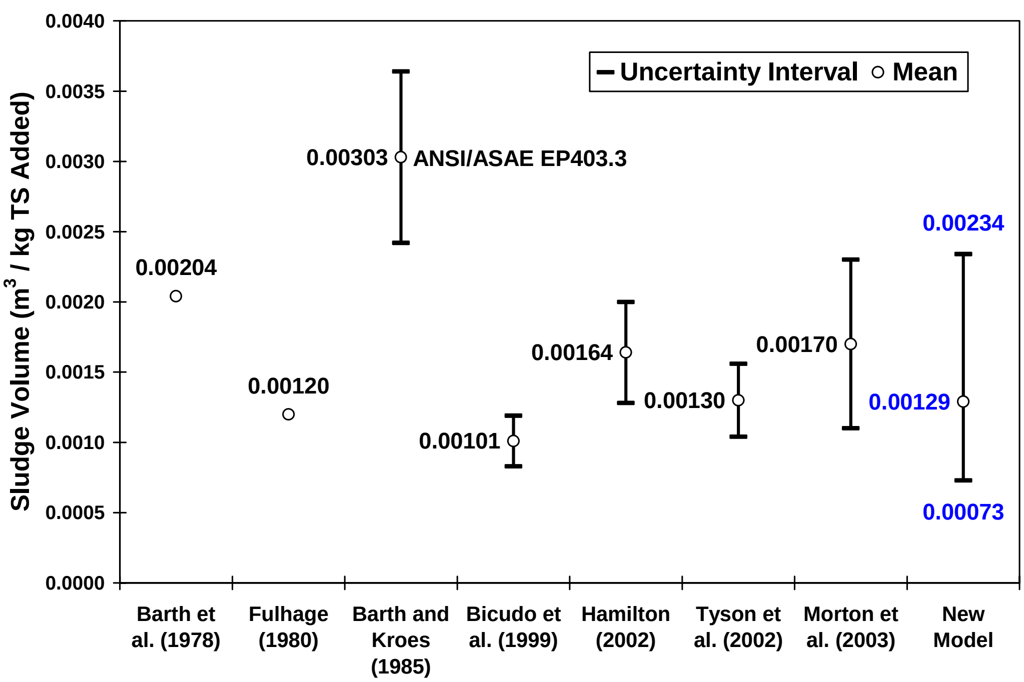

Figure 5. Comparison of sludge volume data and estimates in terms of m^3/kg TS Added for swine lagoons.

Comparisons for Poultry Lagoons

Model estimates for lagoon sludge accumulation in poultry lagoons, in terms of m^3/kg TS Added, are compared with the available data in Figure 6. The current standard provides different values for lagoons treating manure from layer and pullet facilities as indicated in Table 1. However, statistical analysis of the original data indicated that such a distinction was not valid. Therefore, the mean and uncertainty interval (S) attributed to Barth and Kroes (1985) in the figure was the result of statistical analysis of their data.

The observed means were slightly higher than the mean predicted by the model. It is believed that extra feed wastage may have been included in the data. The results shown in Figure 6 indicate that the data and the model agree within the uncertainty of the input parameters.

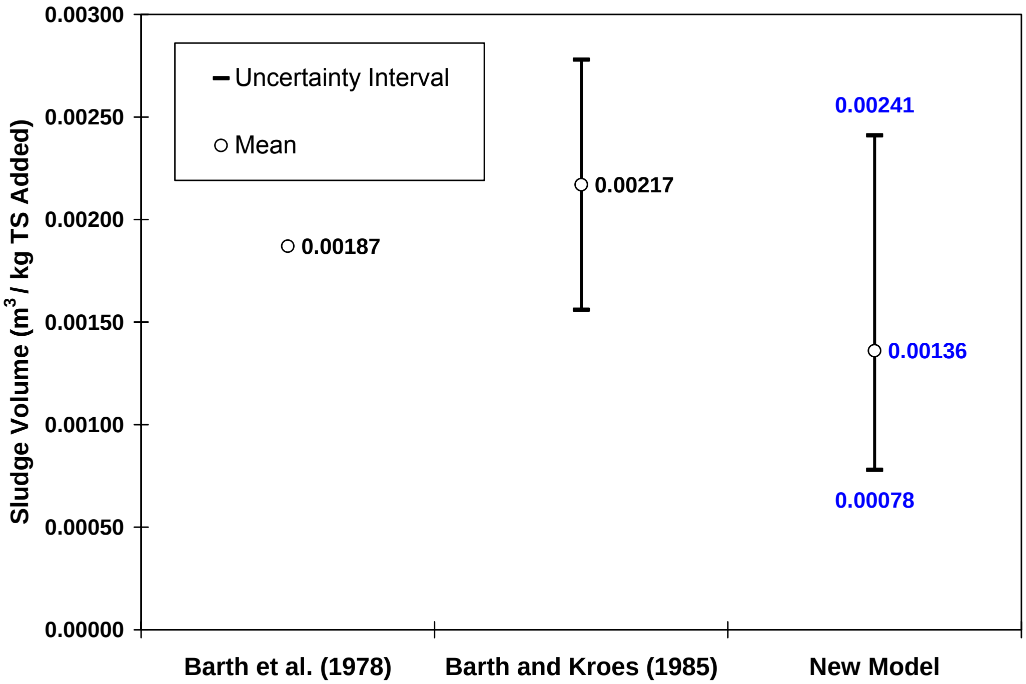

Figure 6. Comparison of model predictions with sludge accumulation data for poultry lagoons.

Comparisons for Dairy Lagoons

Very little information was provided by Barth and Kroes (1985), Barth et al., (1978), and Nordsted and Baldwin (1975) concerning the design and management of the dairy housing facilities that were used with the lagoons studied. All of the dairy facilities were built before 1980 and the vast majority were located in South Carolina.

During the late 1970's, most of the freestalls in South Carolina were bedded with chopped organic bedding of some type. The organic bedding would be kicked out of the stalls by the cows and was included in the manure that was removed from the facility and loaded into the lagoon. It was also common for dairy producers to allow cows to have daily access to paddocks or dirt lanes that led to pastures. As a result, soil would be brought into the freestall facility by the animals and a significant amount of soil would enter the lagoon with the manure. Therefore, estimation of the sludge buildup rates in lagoons treating dairy manure must include the solids from organic bedding and the soil tracked in by cows.

None of the studies of sludge accumulation for dairy lagoons included the solids loading associated with organic bedding or soil. The only solids considered by Barth and Kroes (1985), Barth et al. (1978), and Nordsted and Baldwin (1975) were solids from the manure and a small amount of feed wastage (5%). As a result, the sludge accumulation rates expressed in terms of m^3/kg TS Added in the literature and the current standard (*ASAE Standards*. 2004) cannot be compared with the model.

Barth (1985) provided tabulated values of dairy manure production based on excreted manure and 5% feed wastage. The value used was 9.4 g TS_M / kg_{LAW}-day.

All of the sludge volumes provided in terms of m^3/kg TS Added were converted to m^3 / kg_{LAW} -yr using the solids production value provide by Barth (1985). These values were provided previously in Table 9.

Estimates of sludge accumulation for dairy lagoons were made for three cases. The first assumed that only manure solids and a small amount of wasted feed (5%) was loaded into the lagoon (9.4 gTS_M / kg_{LAW}-day, f_{FW} = 1). The second case assumed that bedding solids were included with the manure at the rate of 3 gTS / kg_{LAW}-day. Thus, the total solids loading was 12.4 gTS / kg_{LAW}-day (equation 4). The third case included fixed solids from soil at the rate of 1.5 gFS_{SOIL} / kg_{LAW}-day. The soil was included as MFS_{SOIL} in equation 2, and the total solids loaded was 13.9 gTS / kg_{LAW}-day.

Model estimates for all three cases are compared with dairy lagoon sludge accumulation data from five lagoons in terms of m^3 / kg_{LAW}-yr in Figure 7. The results shown in the figure indicate that including solids from organic bedding and soil greatly improved the agreement between the model and the data. The data and the model predictions that included bedding and soil agreed within the uncertainty of model parameters.

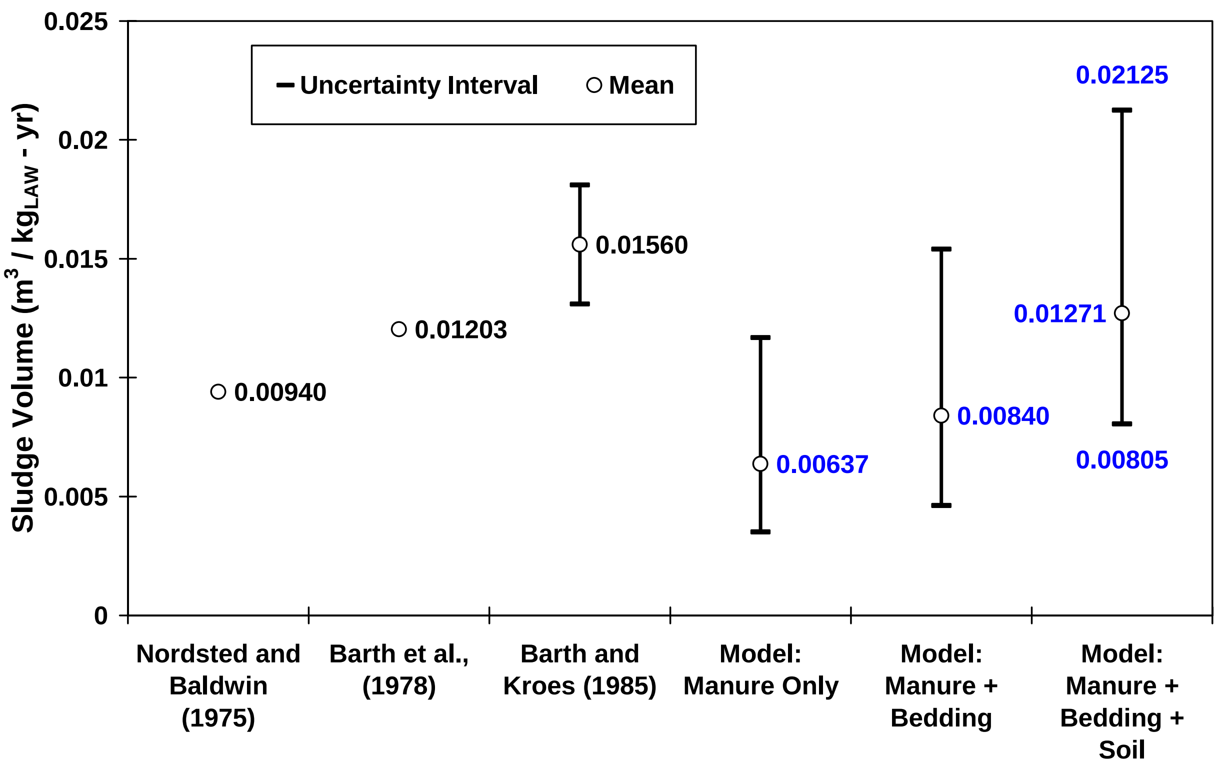

Figure 7. Comparison of model predictions with sludge accumulation data for dairy lagoons.

The weighted average sludge accumulation rate for the five dairy lagoons was 0.01365 m^3 / kg_{LAW}-yr. Using a total solids loading of 13.9 gTS / kg_{LAW}-day the sludge accumulation rate of the five lagoons was 0.00269 m^3 / kg TS Added. The average sludge accumulation rate for the model was 0.00251 m^3 / kg TS Added - a difference of only 6.7%.

Conclusions

A new model to estimate sludge accumulation in animal manure treatment lagoons was developed based on application of a mass balance to the sludge layer (equations 2, 3, and 4). The input parameters describe settling, destruction of volatile solids, and accumulation of soil.

Comparison of model results with the available data and sludge accumulation rates used in the current ASABE standard (ANSI/ASAE EP403.3, *ASAE Standards,* 2004) indicated the following.

- The new model predicted the majority of the available lagoon sludge accumulation data within the uncertainty of the input parameters.
- Currently, two sludge accumulation rates are given in ANSI/ASAE EP403.3 (*ASAE Standards,* 2004) for layers and pullets. Statistical analysis of the original data and model results indicated that such a distinction is not warranted.
- The current sludge accumulation rate for dairy lagoons was based on an underestimation of the total solids loaded per day. Unlike the new model, the sludge volume estimation provided by the current standard does not include the contributions of bedding or soil to the sludge layer.
- Using constant sludge accumulation rates is not adequate for lagoon design.
- The new model provides a simple, flexible method that allows the practicing engineer to implement site-specific data, and professional judgment.

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