SEEPAGE LOSSES FROM ANIMAL WASTE LAGOONS: A SUMMARY OF A FOUR–YEAR INVESTIGATION IN KANSAS

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ABSTRACT. *Seepage losses from animal waste lagoons can affect groundwater quality if liquid effluent is not properly contained within the basin. Seepage rates from 20 anaerobic lagoons were measured using water balance methods. Study locations included 14 swine sites, 5 cattle feedlots, and a single dairy. Seepage results and basin geometry were used to estimate the hydraulic conductivity (K_s) of the compacted soil liner at each site. Seepage data and waste chemistry were used to calculate rates of chemical export into the vadose zone. Profiles of ammonium–nitrogen (N) and other chemicals were determined by sampling soils beneath old lagoons.*

Seepage rates from 20 lagoons averaged 1.1 mm/d and ranged from 0.2 to 2.4 mm/d. Fifteen of the 20 lagoons had seepage rates between 0.5 and 1.5 mm/d. The variation among locations was small despite large differences in soil types and depths to groundwater. On average, the K_s of lagoon liners was 1.8×10^{-7} cm/s. Variation in seepage rates and K_s among sites was lognormally distributed. There was evidence that seepage was moderated by the organic sludge that blankets the bottom of lagoons. Concentrations of nitrogen, phosphorus, and other waste constituents were, on average, 3 to 5 times higher in swine waste lagoons compared to cattle feedlot lagoons. Ammonium–N seepage into the subsoil ranged from 2000 to 5000 kg ha^{-1} yr^{-1} at the larger swine sites but averaged 385 kg ha^{-1} yr^{-1} at cattle feedlots. Soil cores showed that concentrations of ammonium–N, organic–N, phosphorus, and other cations were highest near the original floor of the lagoon but decreased markedly with depth. In most cases, concentrations of nutrients in the soil returned to background levels about 3 m under the lagoons. Additional research is needed on fate and transport of contaminants that accumulate beneath lagoons and best management practices for lagoon closure.

Keywords. *Animal feeding operations, Groundwater quality, Anaerobic lagoons, Manure storages, Compacted soil liners.*

Anaerobic lagoons and earthen storage ponds are used to treat and store manure waste at animal feeding operations (AFOs). Most lagoons are soil–lined basins between 0.5 and 2.5 ha in area and 2 to 6 m deep. Compacted soil liners, between 0.3 m and 0.46 m thick, are designed to keep seepage rates less than some legally specified value (e.g., 3 mm/d). However, seepage rates from earthen storages are not zero, and lagoons contain nutrients, salts, pathogens, and other chemicals that could contaminate drinking water. These concerns have led some to suggest that animal waste lagoons should have plastic liners or that anaerobic waste treatment using lagoons should be abandoned completely. However, most other forms of waste storage are more costly than earthen lagoons. Thus, there is a need for careful assessment of the relationship between lagoon use and groundwater quality before any new restrictions are applied. Unfortunately, seepage from existing lagoons is rarely measured, and studies of contaminant transport beneath lagoons are uncommon. This article summarizes the findings from a four–year lagoon study conducted in Kansas and reviews implications of the results.

Article was submitted for review in August 2001; approved for publication by the Soil & Water Division of ASAE in March 2002.

Contribution no. 02–47–J from the Kansas Agricultural Experiment Station, Manhattan, Kansas.

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Detailed reviews of research on lagoon seepage have been summarized previously (Ham and DeSutter, 1999, 2000; Parker et al., 1999); only a brief review of the most crucial findings will be presented here. It is difficult to predict seepage from earthen storages because of the complex group of variables that affect flow through the compacted liner (Daniel, 1984). Studies clearly show that the hydraulic conductivity of many soil liners is reduced by the organic sludge that blankets the bottom of the lagoon (Chang et al., 1974; Daniel and Bouma, 1974; Hills, 1976; Culley and Phillips, 1989; Barrington and Madramootoo, 1989). A recent laboratory study by Maulé et al. (2000) showed that swine waste reduced flow through compacted liners by 2 or 3 orders of magnitude and that this effect was independent of soil liner texture. In the Maulé study, flow was restricted by a thin, 3– to 8–mm thick "black layer" that developed at the liner–sludge interface and reduced the effective hydraulic conductivity of the whole liner to approximately 1×10^{-7} cm/s. Similar results were obtained by Hills (1976), who showed that dairy waste caused large reductions in flow through liners during the initial 16 weeks of waste additions. Both Maulé et al. (2000) and Hills (1976) concluded that reductions in flow were caused by clogging of soil pores at the uppermost portion of the liner. Under field conditions, however, processes such as freezing–thawing, erosion, macropore formation, and wetting–drying may compromise the liner along the shoreline and cause greater seepage into side embankments (Kim and Daniel, 1992; McCurdy and McSweeney, 1993; Parker et al., 1995).

  ISSN 0001–2351

Field measurements of seepage at existing lagoons are needed to integrate all the factors that may be affecting the liner. Ham (1999) showed that seepage rates from lagoons could be measured to within ±0.2 mm/d using short–term water balance experiments. Using these methods, Ham and DeSutter (2000) found the average seepage rate from 7 swine lagoons and 2 cattle lagoons was 1.3 mm/d when the average waste depth was 3.5 m. A field study of 12 lagoons and 15 slurry pits in Iowa found a mean loss rate of 1.2 mm/d when the waste depth was 1.8 m (Glanville et al., 1999). The Iowa study, which used nighttime data only, did not include losses from evaporation and consequently may have overestimated actual seepage.

The fate of contaminants that seep from lagoons has been studied by sampling groundwater near operations or by sampling soils beneath older, closed facilities. Ham and DeSutter (2000) gave examples of six studies in the literature that showed how nutrients or bacteria from animal waste lagoons had contaminated nearby groundwater. All of these sites had shallow water tables (2 to 6 m) and soils with low clay contents in the vadose zone. The importance of soil properties beneath lagoons is demonstrated further by examining chemical profiles beneath old facilities (Miller et al., 1976; Culley and Phillips, 1989; Maulé and Fonstad, 1996; Perschke and Wright, 1998). Most studies show that concentrations of ammonium–nitrogen (N) and other cations are very high near the compacted liner, and then decrease with depth. Anions like chloride, which are not adsorbed by soil clays, penetrate to much deeper depths. Clearly, the risk of groundwater contamination is not only dependent on the seepage rate, but is governed by the chemical concentrations in the waste, depth to the water table, and under–basin soil properties. Ham and DeSutter (2000) argued that site–to–site variation in these properties is so great that lagoon design should be site specific and proposed a logical framework for arriving at custom lagoon specifications for any location.

This article revisits and expands on previous findings concerning lagoons by summarizing data from a four–year study conducted in Kansas. The objective was to provide a comprehensive summary of water balance, waste chemistry, and soils data from lagoons serving a range of AFO types across the state. In contrast to a case study, this article examines a large, multifaceted dataset to arrive at more general conclusions about lagoon seepage and its potential impact on water quality. Data include: (1) measurements of whole–lagoon seepage from 20 existing lagoons, (2) estimates of areally averaged liner hydraulic conductivity, (3) a survey of lagoon waste chemistry at over 40 locations, and (4) analysis of soil cores collected beneath old lagoons that had been closed or were being cleaned. Approximately 80% of the data has not been reported previously.

Methods

Whole–Lagoon Seepage

Whole–lagoon seepage rates were measured at 14 swine waste lagoons, 5 cattle feedlot lagoons, and one dairy. All study sites were in Kansas except one swine site located in central Oklahoma. The study sites were distributed widely across the state: 650 km separated the easternmost and westernmost locations. The swine sites had barns with slatted floors, under–floor concrete pits, and pull–plug waste handling schemes that routed waste into soil–lined lagoons. Cattle feedlot lagoons and the dairy site collected runoff from precipitation that fell on open–air pens. The dairy lagoon also received waste from the milking barn washout. Lagoons had compacted soil liners between 0.15 and 0.46 m thick; several liners had been augmented with bentonite. The size and depth of the lagoons are given in table 1.

Seepage was measured at all 20 sites using the water balance techniques of Ham (1999) and Ham and DeSutter (1999). Briefly, seepage was determined from measurements of evaporation and changes in depth when all other waste inputs and outputs were precluded or quantified. In most cases, data were collected for 5 to 10 days, and the seepage rate (S), in mm/d, was calculated as:

$$S = (P - \Delta D - \Sigma E) / \Delta t \qquad (1)$$

where

P = total precipitation (mm)

$\Delta\Delta$ = total change in depth (mm)

ΣE = cumulative evaporation (mm)

$\Delta\tau$ = duration of the test (d).

Depth change was defined as negative when waste levels were declining; all other variable were defined as positive numbers. Evaporation was measured using the bulk transfer method as described by equation 3 in Ham (1999). Evaporation was computed every 30 minutes as:

$$E = \frac{0.622}{R_d T_s}\left(e_s^* - e_a\right) U_r C_e \qquad (2)$$

Table 1. Whole–lagoon seepage rates from 20 animal waste lagoons. Also included are the type, age, depth, and area of each basin. The apparent hydraulic conductivities of the soil liners were calculated from the whole–lagoon seepage results.

Lagoon	Species	Lagoon Age (yr)	Waste Depth (m)	Lagoon Area (ha)	Seepage Rate (mm/d)	Hydraulic Conductivity (cm/s)
1	Swine	1	1.2	1.5	0.6	1.89×10^{-7}
2	Swine	3	5.3[a]	2.2	0.8	4.44×10^{-8}
3	Swine	6	0.9	0.8	0.8	2.31×10^{-7}
4	Swine	1	1.5[a]	0.5	0.8	1.54×10^{-7}
5	Swine	3	5.6	1.2	0.8	9.81×10^{-8}
6	Swine	4	5.4[a]	2.2	0.9	1.03×10^{-7}
7	Swine[b]	10	1.2	0.5	0.9	2.08×10^{-7}
8	Swine	4	2.4[a]	0.3	1.0	1.71×10^{-7}
9	Swine	5	2.1	0.5	1.3	1.88×10^{-7}
10	Swine[b]	10	1.2	2.0	1.3	3.01×10^{-7}
11	Swine	3	5.5[a]	0.7	1.4	1.54×10^{-7}
12	Swine	4	4.9[a]	2.9	1.5	2.00×10^{-7}
13	Swine	4	5.5[a]	2.4	1.7	1.61×10^{-7}
14	Swine	4	5.8[a]	2.3	2.0	3.70×10^{-7}
	Swine avg.	5	3.9	1.6	1.2	1.84×10^{-7}
15	Cattle	11	2.3	1.8	0.2	4.34×10^{-8}
16	Cattle	15	1.1	0.4	0.6	1.49×10^{-7}
17	Cattle	25	1.6[a]	0.2	0.7	1.28×10^{-7}
18	Dairy	1	2.1	0.2	0.9	1.31×10^{-7}
19	Cattle	14	1.8[a]	1.1	1.0	2.00×10^{-7}
20	Cattle[b]	15	1.2	2.8	2.4	3.09×10^{-7}
	Cattle avg.	14			1.0	1.60×10^{-7}
Overall Mean	All species	8	3.0	1.4	1.1	1.77×10^{-7}

[a] Near maximum capacity.
[b] Second or third stage lagoon.

where

e_s^* = saturation vapor pressure at the temperature of the water surface (Pa)

e_a = vapor pressure of the air (Pa)

R_d = gas constant (287.04 J kg^{-1} K^{-1})

T_s = temperature of the surface (K)

U_r = wind speed at 1 m (m/s)

0.622 = ratio of the molecular weights of water and dry air

C_e = bulk transfer coefficient (dimensionless, 2.8 × 10^{-3}).

Meteorological instruments were positioned 1 m above the liquid surface near the center of the lagoon using a buoy or raft. Measurements included air temperature, humidity, wind speed, global irradiance, and an infrared measurement of waste surface temperature. Precipitation was measured using a tipping–bucket rain gauge positioned on the bank of the lagoon. Precipitation was zero or less than 1 mm during all 20 tests. Depth changes were measured with float–based water level recorders with resolutions of 0.16 mm (Ham and DeSutter, 1999). All instruments were sampled every 10 s using Campbell Scientific data acquisition equipment (Logan, Utah). Data were stored as 30–min averages and transferred to Kansas State University on a daily basis via cellular telephone. To reduce uncertainty in the estimate of *S*, water balance experiments were only performed when evaporation was less than 6 mm/day (Ham, 1999).

Apparent Liner Hydraulic Conductivity

Results from the seepage test were combined with data on liner thickness and basin geometry to calculate the apparent hydraulic conductivity of the compacted liners at all 20 lagoons. Coupling seepage results to liner hydraulic properties requires assumptions regarding saturated flow. Assuming vertical, steady–state flow and zero pressure potential on the bottom of the liner (Rowe et al., 1995; Kisch, 1959), then flow at some position *x*,*y* in the lagoon can be described with Darcy's law:

$$q(x,y) = -K_s\left(\frac{H}{L}+1\right) \tag{3}$$

where

q = flux (m s^{-1})

K_s = hydraulic conductivity (m s^{-1})

H = depth of waste (m)

L = thickness of the compacted liner (m)

all at horizontal position *x*,*y*.

If we assume K_s is homogeneous, then the seepage rate from the whole lagoon is related to the total flux across the liner:

$$Q = S'A = \iint q(x,y)\,dx\,dy \tag{4}$$

where

Q = whole–lagoon seepage rate (m^3 s^{-1})

S' = seepage rate expressed as a rate change in depth (m s^{-1})

A = area of the liquid surface (m^2).

Assuming K_s is homogeneous and constant, then K_s can be removed from the integral, and the right side of equation 4 is essentially determined by the geometry of the lagoon basin and depth of waste. For a simple rectangular lagoon with a flat bottom and sides with the same slope, equation 4 can be reduced to a simple form:

$$S' = \frac{K_s}{A}\left[A_s\left(\frac{H'}{2L}+1\right)+A_b\left(\frac{H'}{L}+1\right)\right] \tag{5}$$

where

H' = waste depth above the bottom of the lagoon (m)

A_s = areal area of the submerged side embankments (m^2).

A_b = areal area of the flat bottom (m^2).

Equation 5 assumes that the vertical pathlength through the liner is the same on the sides and bottom. Equation 5 was rearranged to estimate the apparent K_s of the liner at the 20 lagoons where seepage tests were performed. Data on liner thickness was not available at eight locations; in these cases, a liner thickness of 0.3 m was assumed.

Waste Chemistry and Soil Sampling

Lagoon effluent was sampled at 20 swine sites and 20 cattle feedlots. Samples were taken using zero–contamination techniques, and the effluent was analyzed for various chemical and physical parameters by Servi–Tech Laboratories, Dodge City, Kansas, or by the Kansas State University Soil Testing Laboratory, Manhattan, Kansas. At some locations, sampling was repeated several times during the year to check for seasonal fluctuations. A 1.2–L Kemmerer sampler was used to collect samples at multiple depths within several lagoons. No evidence of vertical stratification was found unless the sampler was lowered into the sludge layer on the bottom of the basin. Thus, liquid samples were collected only from the lagoon surface at most sites. The export rate of nitrogen and chloride were computed for all 20 lagoons where seepage was measured. Export was assumed to be the product of the seepage rate and the corresponding chemical concentration at the same lagoon.

Soil cores were collected beneath several old lagoons in Kansas using direct–push soil–sampling equipment. Study sites included four cattle feedlots, a dairy site, and two swine sites. Lagoon age ranged from 10 to 25 years. In most cases, soil cores were collected from the bottom of the basins within a month after the lagoons had been dried and the manure sludge removed. Core samples extended from the top of the compacted liner to depths of 3 to 5 m. When possible, soil cores were collected at multiple locations in each lagoon. Samples were analyzed for a wide range of nutrients, salts, and physiochemical properties (e.g., cation exchange capacity). A more detailed study was conducted at an 11–year–old cattle feedlot, a site where four deep cores were collected along a 120–m transect that extended the length of the basin.

Results

Water Balance Test Example

To demonstrate how seepage was computed for the 20 lagoons in the study, data from a water balance test at a cattle feedlot are presented in figure 1. Data were collected over a 5–day period starting on 28 March 2001, and only trace precipitation (0.3 mm) was recorded during the test. A float–based recorder and a pressure probe (PTX1830, Druck Inc., New Fairfield. Conn.) were used to measure changes in depth, and evaporation was estimated using equation 2. Excellent agreement was observed between the float– and pressure–based water level recorders (fig. 1a). At the end of the test period, the float–based recorder reported a change in depth of 16.3 mm, while the pressure probe recorded

16.5 mm. Cumulative evaporation over the 5–day period was 11.48 mm. Using the accumulated data at the end of the test, the total seepage was 5.1 mm, resulting in a calculated seepage rate of 1.02 mm/day. Figure 1b shows the seepage rate that would have been computed if the test had been stopped hypothetically at different times during the study. This "moving" seepage calculation is like a running mean that incorporates the cumulative results from the start of the test. The estimate of seepage approached 1 mm/d after about 48 h of data collection and was very stable throughout the remainder of the test. The consistency of the seepage estimate over time was a good indication that errors surrounding $\Delta\Delta$ and E were small. Figure 1 demonstrates that water balance methods do not require long periods of data collection when equipment with high resolution is employed. As with all measurements, there is some uncertainty surrounding the seepage estimates. Ham (1999, 2002) showed that seepage could be estimated to within ±0.2 mm/day when evaporation rates are low. More detailed information on the water balance technique is provided elsewhere (Ham, 1999, 2002; Ham and DeSutter; 1999).

Seepage Rates and Liner Properties at 20 Lagoons

Seepage rates from the 14 swine waste lagoons ranged from 0.6 to 2.0 mm/d with an overall average of 1.2 mm/d (table 1). Data from the cattle waste lagoons were similar with an average of 1.0 mm/d. The overall lagoon seepage rate for swine and cattle was 1.13 mm/d when the average liquid depth was 3 m. These results are similar to the 1.2 mm/d average seepage rate reported in the Iowa lagoon study of Glanville et al. (1999). The range of seepage values was remarkably small considering the differences among sites. Site–to–site variation in seepage and liner conductivity probably can be described by the lognormal distribution. Parkin et al. (1988) showed that many soil properties, including K_s, are distributed lognormally and presented the proper equations for computing the mean, variance, and standard deviation for the distribution.

Figure 2a shows a histogram of the seepage results in table 1 and the theoretical lognormal distribution computed using equations 4 through 8 from Parkin et al. (1988). The mean and standard deviation of the 20 sites were used as inputs to the probability density function. By graphical inspection, the lognormal distribution appeared to be an apt description of the data. Lognormality also was confirmed by calculation of the Kolmogorov and Cramer Von Mises statistics, as described by Rao et al. (1979). Both the histogram and the distribution suggest that most lagoons will have seepage rates between 0.5 and 1.5 mm/d. Assuming the data in table 1 is representative of Kansas, the cumulative probability function (fig. 2b) allows the following conclusions about the population of all lagoons in the state: (1) 75% of all lagoons have seepage rates between 0.3 and 1.6 mm/d, (2) 95% of all lagoons seep less than 2.7 mm/d, and (3) only 15 % of lagoons seep less than 0.5 mm/d.

Variance in the seepage data included the effect of liner conductivity, depth of waste, and geometry of the basin. To account for these effects and get a better comparison of liner performance among sites, the apparent liner conductivity was computed using equation 5. The apparent coefficient of permeability ranged from 4.3×10^{-8} to 3.7×10^{-7} cm/s with an overall average of 1.8×10^{-7} cm/s. These results are similar to the laboratory tests of Maulé et al. (2000) and Hills

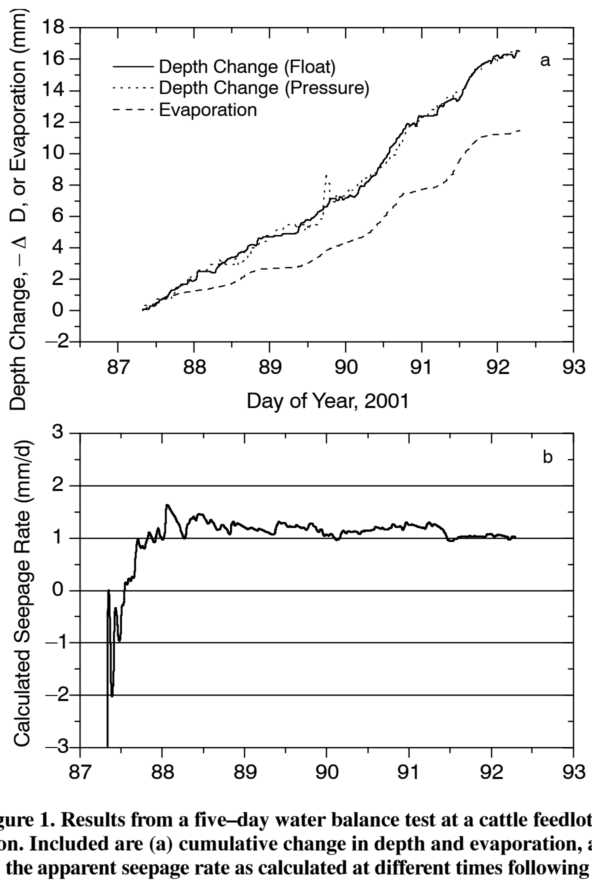

Figure 1. Results from a five–day water balance test at a cattle feedlot lagoon. Included are (a) cumulative change in depth and evaporation, and (b) the apparent seepage rate as calculated at different times following the start of the test. Changes in depth were measured with float– and pressure–based recorders.

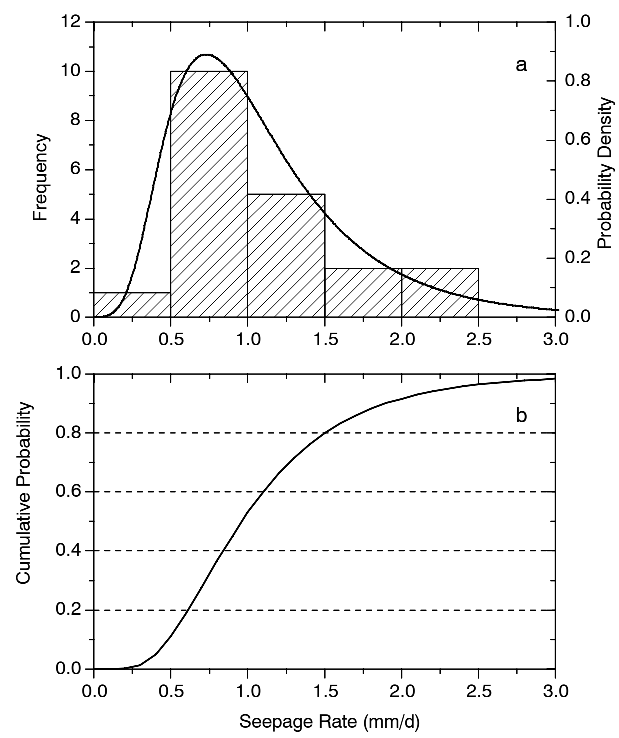

Figure 2. Histogram of the whole–lagoon seepage rates measured from 20 lagoons (table 1). Also shown are (a) the probability density curve and (b) the cumulative probability curve for the lognormal distribution as calculated from the mean and variance of the seepage data.

(1976). Unexpectedly, the coefficient of variation (CV) for the conductivities was 0.59, slightly higher than CV for the seepage data, 0.57. It was thought equation 5 would reduce variance by removing depth effects.

The whole–lagoon conductivities in table 1 were compared to soil liner conductivities at 105 sites in Kansas that had been sampled by the Natural Resources Conservation Service (NRCS). The NRCS data were from intact cores or disturbed samples that had been collected mostly from newly constructed animal waste lagoons (i.e., before waste additions), but some samples were from foundations for dams and other structures. Laboratory analysis of the soil samples was preformed at the NRCS Soil Mechanics Center in Lincoln, Nebraska. When computed assuming a lognormal distribution, the conductivities of the NRCS samples had a larger mean (3.7×10^{-5} cm/s) and much higher variance compared to whole–lagoon conductivities in table 1. A higher variance is expected in the soil core data because they include the effect of within–lagoon spatial variability in liner properties. Figure 3 shows the cumulative probability functions for both sets of samples. The whole–lagoon analysis indicated that most liners would have conductivities between 1.0×10^{-7} and 3×10^{-7} cm/s. Virtually no conductivities less than 0.5×10^{-7} cm/s or greater than 4.0×10^{-7} cm/s are expected. These results again agree very well with results of Maulé et al. (2000) and Hills (1976). Conversely, the NRCS soil core analysis showed a huge range of conductivities. The distribution predicts that 20% of the conductivities will be less than 0.5×10^{-7} cm/s and 50% will be greater than 4×10^{-7} cm/s. Figure 3 demonstrates the fundamental problem with trying to use data from laboratory analysis of soil cores to predict seepage through compacted lagoon liners in the field. In a working lagoon, it is likely that sludge greatly reduces the conductivity of liners that initially (i.e., before waste inputs) have higher conductivities ($>4.0 \times 10^{-7}$); this is exactly what Hills (1976) demonstrated in the laboratory. Conversely, imperfections during construction and processes that promote side seepage (erosion, etc.) make it difficult to build a compacted liner that has an areally–averaged conductivity less than 1×10^{-7} cm/s. Note that 1×10^{-7} cm/s is the same conductivity reported in the experiments of Maulé et al. (2000) and Cully and Phillips (1989), experiments where side seepage was precluded. It is likely that the bottom of most lagoons, including side slopes that are submerged and sludge laden, have conductivities near 1×10^{-7} cm/s, while the sides of the lagoon have some greater conductivity.

It is not surprising that the variance in seepage rates among lagoons is small. Manure that has undergone anaerobic digestion in a lagoon probably has some fairly standard particle size distribution. Soils also have a pore size distribution that is affected by texture and compaction. The process of sedimentation, bridging, and clogging results in a thin, sludge–affected layer, 3 to 8 mm thick, on the top of the liner. Maulé et al. (2000) showed that this layer has a very low conductivity, near 3×10^{-9} cm/s. The effective conductivity of the entire liner is then the combined effect of the sludge–affected layer and the underlying compacted–soil layer. Mathematically, the apparent hydraulic conductivity of the entire liner is the harmonic mean of these two layers (Rowe et al., 1995).

Although it is very thin, the sludge–affected layer will dominate the overall conductivity of the liner when its

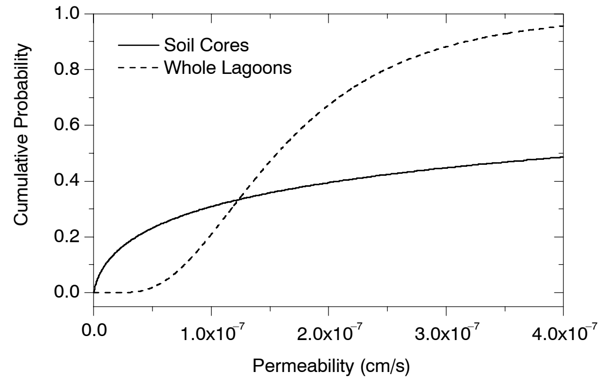

Figure 3. Cumulative probability for the hydraulic conductivity (K_s) of soil liners using the lognormal distribution. One curve was calculated using the mean and variance of liner conductivity as computed from the whole–lagoon seepage measurements (table 1). The second curve represents laboratory analysis of 105 soil cores collected from compacted liners at various lagoon, dam, and pond sites in Kansas.

conductivity is much smaller than that of the compacted–soil layer. This is probably the case at most lagoons. The relative importance of the sludge–affected layer diminishes as the conductivity of the compacted–soil layer decreases. Thus, the sludge layer will probably have little effect on lagoon seepage if a basin is built with a thick liner made of heavy clay. On the other extreme, if the operator simply excavates a pit and starts adding waste, then the sludge will probably cause a dramatic decrease in conductivity over the first few weeks of operation. This moderating effect of the sludge, which is weighted based on initial liner properties, tends to reduce the variance in seepage rates among sites.

If the sludge–affected layer has a conductivity much lower than the compacted soil liner, then it is possible that unsaturated conditions may exist in the liner itself. This is an important consideration because all Darcy's law approximations of seepage (eq. 3), as well as laboratory permeameter testing, are done assuming that the liner is saturated. If conditions are unsaturated in the lower portion of the liner and the underlying subsoil, then the overall conductivity of the layered system also will be reduced. The lack of saturation will not only depend on hydraulic properties but also on the depth of waste and the distance to the water table, both of which can fluctuate over time. Unsaturated conditions in compacted liners deserve further study and could have important consequences on the fate and transport of contaminants beneath lagoons (Maulé and Fonstad, 1996).

Chemistry of Lagoon Effluent and Subsurface Chemical Export Rates

Waste chemistry is a crucial aspect of assessing environmental risk, especially for soluble compounds (e.g., ammonium–N, chloride, etc.), because the rate of contaminant loading on the subsoil is the product of chemical concentration and the seepage rate. There were large differences in waste chemistry between sites and between species (table 2). Ammonium nitrogen ranged from 10 mg/L at a cattle feedlot to as high as 3540 mg/L at an ice–covered swine lagoon, but there were large variations within species as well. The median ammonium–N concentrations were 734 mg/L at swine sites and 170 mg/L at cattle feedlots. On average, total nitrogen and phosphorous were about three times higher in the swine lagoons compared to the cattle sites. Chloride

Table 2. Chemical and physical characteristics of waste from anaerobic lagoons used to contain animal waste.

	Lagoon Type							
	Swine (20 sites)				Cattle (20 sites)			
Measured Parameters	Maximum	Minimum	Average	Median	Maximum	Minimum	Average	Median
NO_3^- –N (mg L^{-1})	1.4	<1.0	<1.0	<1.0	1.0	<1.0	<1.0	<1.0
NH_4^+ + NH_3–N (mg L^{-1})	3540.0	180.0	910.2	734.5	510.0	10.0	171.5	170.0
Total N (mg L^{-1})	4730.0	210.0	1080.0	834.0	785.0	70.0	303.8	285.0
Organic N (mg L^{-1})	1190.0	30.0	169.6	99.0	275.0	30.0	132.7	115.0
Total Phosphorus (mg L^{-1})	1307.0	9.0	150.4	47.5	132.0	18.0	59.3	49.0
Potassium (mg L^{-1})	3621.0	328.0	1098.0	913.5	2172.0	190.0	838.2	659.5
Sulfur (mg L^{-1})	400.0	10.0	56.7	30.0	130.0	10.0	57.5	40.0
Calcium (mg L^{-1})	1400.0	40.0	194.8	99.5	435.0	90.0	208.1	190.0
Magnesium (mg L^{-1})	338.0	6.0	41.4	18.0	181.0	42.0	102.1	96.5
pH	8.5	6.5	8.1	8.2	8.1	7.1	7.8	7.8
Sodium (mg L^{-1})	970.0	90.0	329.3	290.5	740.0	50.0	268.5	206.0
Chloride (mg L^{-1})	2007.0	195.0	497.4	304.5	1956.0	131.0	652.6	549.5
BOD[a] (mg L^{-1})	2370.0	860.0	1605.1	1697.0	1871.0	246.0	747.6	522.5
COD[b] (mg L^{-1})	3066.0	1550.0	2603.0	2898.0	2338.0	1710.0	1927.3	1734.0
TSS[c] (mg L^{-1})	420.0	140.0	283.3	270.0	2540.0	240.0	1016.0	694.0
EC[d] (mmho cm^{-1})	28.0	2.7	8.9	8.0	10.2	1.7	5.5	4.6
TDS[e] (mg L^{-1})	17920.0	1747.0	5783.3	5075.0	6528.0	1056.0	3586.1	2694.0
SARa[f]	35.3	8.7	21.8	21.1	30.2	2.8	12.2	10.2

[a] BOD = biological oxygen demand.
[b] COD = chemical oxygen demand.
[c] TSS = total suspended solids.
[d] EC = electrical conductivity.
[e] TDS = total dissolved solids.
[f] SARa = sodium adsorption ratio (adjusted).

concentrations were 652 and 497 mg/L at cattle and swine sites, respectively. Chloride was higher at cattle feedlots, where ions can accumulate in runoff that traverses large areas of pen space before reaching the lagoons. Biochemical oxygen demand and chemical oxygen demand were about two times higher at swine sites, which reflected the higher concentration of organic matter in the effluent. Total suspended solids were about four times higher at cattle feedlots compared to swine sites. This result probably reflects higher concentrations of clay and silt particles that have been eroded from pen floors during runoff. Finally, the adjusted sodium adsorption ratio (SAR) was about 22 at swine sites and 12.2 at cattle feedlots. Waste with adjusted SAR values greater than 9 is a potential sodium hazard if used for irrigation.

Waste chemistry showed minimal vertical stratification in most lagoons sampled. At swine sites, mixing was promoted by the routine addition of waste and by floating pumps used to recirculate effluent or flush the under–floor pits. Wave action probably contributed to mixing, especially in shallow lagoons (<2 m deep). On occasion, phosphorous concentrations increased if samples were taken close to the sludge layer. Samples of the sludge showed that total phosphorus was about 5%. At several sites, sampling was repeated over time to examine seasonal changes in concentration. At a cattle feedlot, where eight samples were collected over an 18–month period, concentrations of ammonium–N fluctuated from 18 to 170 mg/L. During a two–year sampling period, concentrations of ammonium–N at a large swine finishing operation varied from 711 mg/L to 1050 mg/L.

Export rates of ammonium and chloride, into or through the compacted liner, are shown in figure 4. Export of ammonium–N ranged from 200 to 6000 kg ha^{-1} yr^{-1}. The export rates from cattle feedlots were, on average, 385 kg ha^{-1} yr^{-1}, while the average export rate from the swine sites was 2957 kg ha^{-1} yr^{-1}. Cattle feedlots accounted for 5 of the 7 observations in the first bar of the histogram in fig. 4a. The large difference in export rates between species reflects the differences in waste concentration and the fact that the swine average included four lagoons with export greater than 4000 kg ha^{-1} yr^{-1}. Chloride export was not species dependent, with most sites having loss rates between 1000 and 3000 kg ha^{-1} yr^{-1}. The export rates of chloride may be lognormally distributed. The distribution of seepage rates and chemical concentrations (table 2) could be used to approximate the probability distribution of chemical export (i.e., Monte Carlo simulation). Chemical export rates, which represent the flux boundary condition at the liner, are a crucial parameter for modeling the fate and transport of contaminants under lagoons.

Soil Chemical Profiles Beneath Lagoons and Implications for Closure

Profiles of ammonium–N and organic–N beneath six lagoons are shown in figure 5. The three cattle feedlot lagoons and the dairy lagoon were between 11 to 15 years old. These four sites were sampled when the lagoons had been dewatered for cleaning. The two swine sites (figs. 5d and 5e) were 20 to 25 years old and were no longer in use. Although decommissioned, the residual manure sludge from the old lagoons was removed only a few days prior to sampling. These lagoons served small operations and were not representative of modern, large–scale, swine production sites. Soil properties varied among the sites, and by position and depth within each basin. In general, most sites had clay contents between 18% and 30% and cation exchange capacities (CEC) between 15 and 25 cmol/kg.

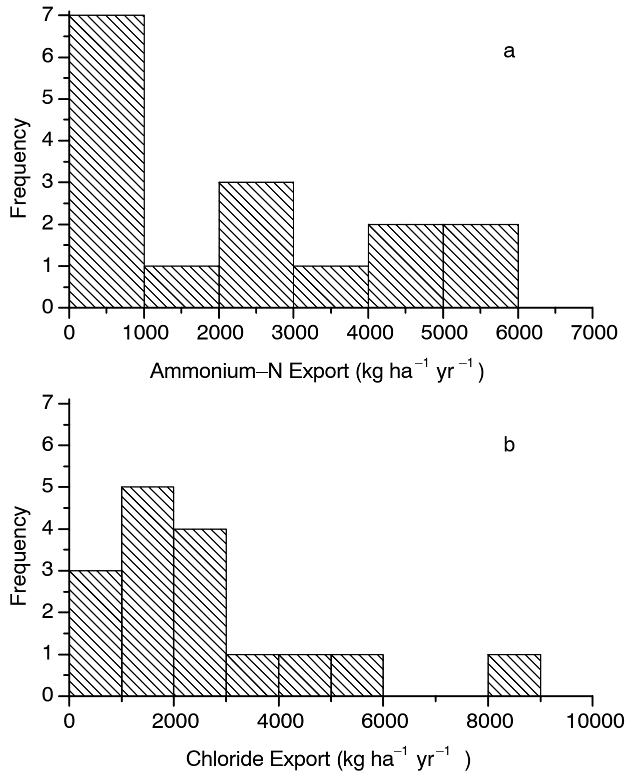

Figure 4. Annual subsurface export rates of (a) ammonium–N and (b) chloride from the 20 lagoons listed in table 1. Data were calculated from the seepage rate and the corresponding chemical concentration of NH_4^+–N and Cl^- in each lagoon.

Figure 5 shows that both ammonium– and organic–N concentrations were the highest near the compacted liners and then decreased with depth. The profiles of ammonium–N were consistent with patterns reported elsewhere (Maulé and Fonstad, 1996; Perschke and Wright, 1998). Ammonium–N is strongly adsorbed to soil clays, and the degree of adsorption is dependent on soil CEC and the concentration of competing cations (Lance, 1972). Calcium and magnesium cations were abundant in both swine– and cattle–lagoon effluent (table 2) and may affect subsurface ammonium–N distributions. The profiles of organic–N were similar in magnitude and pattern to that of ammonium–N. Organic–N represents small solid organic particulate (i.e., manure solids), soluble organic acids, and nitrogen in the microbial biomass. Organic–N may be an overlooked aspect of contaminant transport from lagoons because it could be mineralized into nitrate if oxygen becomes available. The accumulated total nitrogen beneath lagoons is an indication of the history of flux through the liner over time. For example, at the cattle feedlot lagoon shown in figure 5b, total ammonium–N and organic–N beneath the lagoon were 0.37 and 0.46 kg/m^2, respectively. At the swine site in figure 5e, the ammonium–N and organic–N were 1.64 and 1.48 kg/m^2, respectively.

The mass of ammonium–N that will accumulate beneath lagoons can be approximated from the seepage and chemistry data in tables 1 and 2. Calculations were done assuming the ammonium–N concentration was 910 mg/L for swine and 171 mg/L for cattle. Assuming a lagoon will be used for 25 years and has a seepage rate of 1.1 mm/d, the ammonium–N stored under swine and cattle lagoons would be 9.1 and 1.7 kg/m^2, respectively. These levels of accumulation are much greater than that observed for the swine sites in figure 5. It is likely that the ammonium–N under modern swine production lagoons will penetrate to lower depths than observed in figures 5d and 5e. A good example of deep nitrogen penetration is provided by Miller et al. (1976), who detected ammonium–N concentrations above 300 mg/kg at 4.2 m beneath a 10–year–old swine lagoon. Positional variation of liner and soil properties can affect how nitrogen and other contaminants are distributed under lagoons.

Figure 6 shows results from four soil cores that were collected along a 120–m transect at an 11–year–old cattle feedlot lagoon in southwest Kansas. The lagoon had been dewatered and cleaned of sludge prior to sampling. Profiles of ammonium–N and phosphorus (figs. 6a and 6b) showed large variations in concentration among the different locations. As shown in figure 6., concentrations of both cations were higher near the liner and decreased with depth. One exception was core number 4, which was located in an area with a very dense clay layer immediately beneath the compacted liner. It is clear that very little seepage occurred at this location. Chloride, an anion, did not demonstrate the adsorption pattern seen in nitrogen, and concentrations fluctuated between 50 and 80 mg/kg down to 4 m (fig. 6c). Chloride was probably being transported vertically and horizontally to locales well beyond the sampling range shown here. Figure 6d shows the differences in CEC between the coring locations. Cores 3 and 4, located on the east end of the basin, had a much higher CEC and clay content than core 2. This example shows that seepage rates and the adsorption of cations can be very dissimilar at different positions in the lagoon. A sampling scheme is needed that considers spatial variation when assessing the fate and transport of contaminants beneath lagoons.

Data indicate that ammonium–N and organic–N will build up under animal waste lagoons over the life of the facility. A large portion of the nitrogen probably will remain close to the lagoon, especially if soils in the vadose zone contain some clay (e.g., >15%). However, once a lagoon is dewatered and cleaned, the diffusion of oxygen into the contaminated subsoil could promote conversion to nitrate–N. Nitrate–N is highly mobile in the soil and represents a greater environmental hazard. Unfortunately, little research is available on the fate and transport of nitrogen under lagoon closure conditions. Models are needed that can simulate nitrogen movement while accounting for the hydrology, chemical conversions, and microbial nitrogen dynamics in the vadose zone. When lagoons are closed, it may be necessary to excavate some of the nitrogen–laden soil.

CONCLUSIONS

The main conclusions from the Kansas study can be summarized as follows:

- Seepage rates from existing lagoons can be measured effectively to within ±0.2 mm/d using short–term water balance experiments. Therefore, it is feasible to test the performance of lagoons after construction. Because waste has a profound impact on liner performance, seepage tests should be done at least four months after the initial addition of waste.

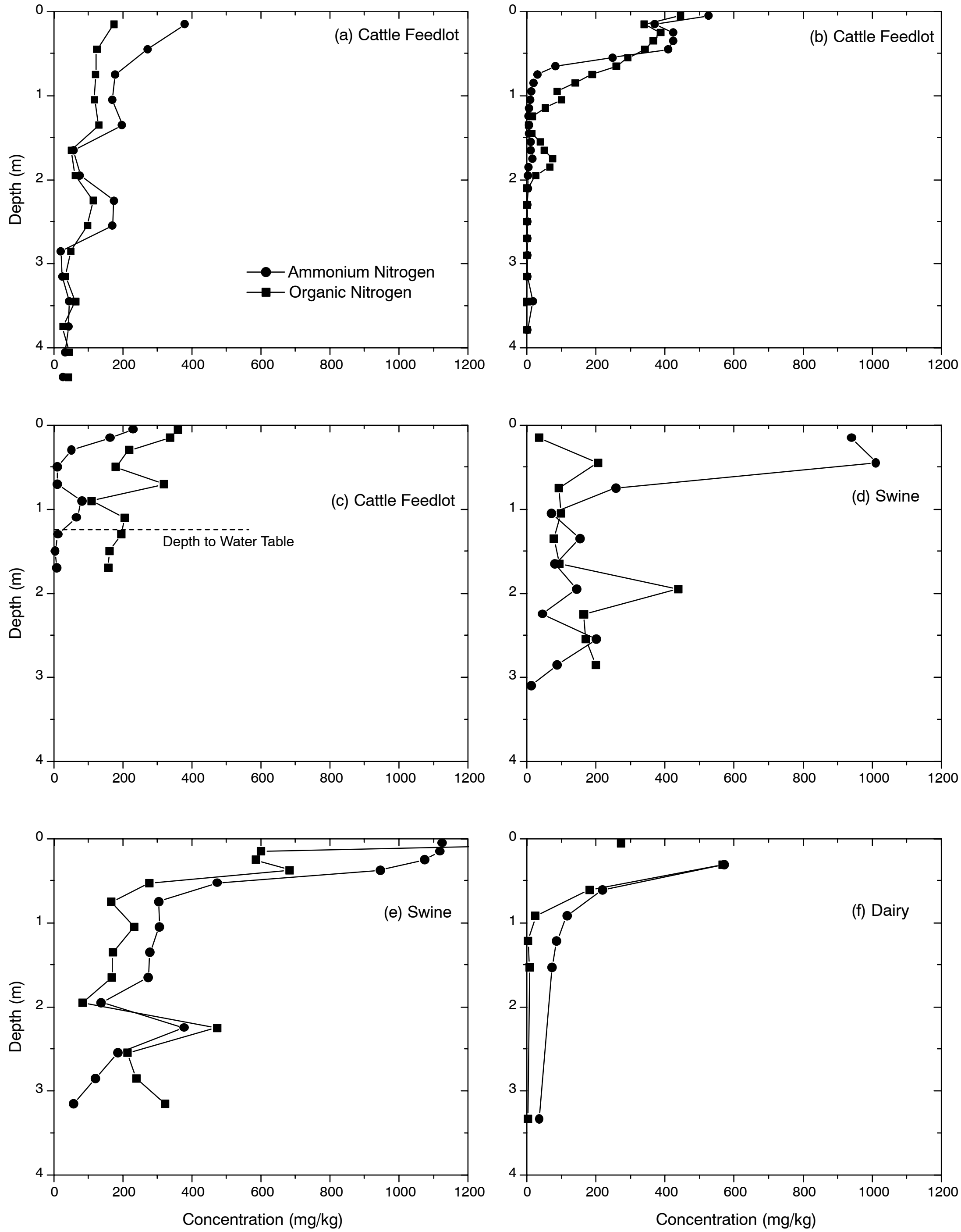

Figure 5. Profiles of ammonium nitrogen and organic nitrogen beneath six older lagoons.

- The average seepage rate from 20 lagoons was 1.1 mm/d; variation among sites appeared to be lognormally distributed with a standard deviation of 0.63 mm/d. Seepage rates from cattle and swine lagoons were not different, although a detailed statistical comparison was not possible.
- On average, the apparent hydraulic conductivity of the soil liners at the lagoons was 1.8×10^{-7} cm/s. Conductivity among sites was lognormally distributed with a variance much lower than would have been predicted from an analysis of soil cores.
- Data suggest that organic sludge reduces flow through the liner that may limit seepage to a very narrow range, especially considering the variation in soils, construction, and management among sites. From the lognormal analysis, it can be hypothesized that 75 % of lagoons in Kansas have seepage rates between 0.3 and 1.6 mm/d. Lagoons in other regions of the Great Plains probably have similar rates of seepage.
- Effluent chemistry among lagoons is highly dependent on species and location. In general, concentrations of nitrogen in the swine waste lagoons were 3 to 5 times higher than that at cattle feedlots.

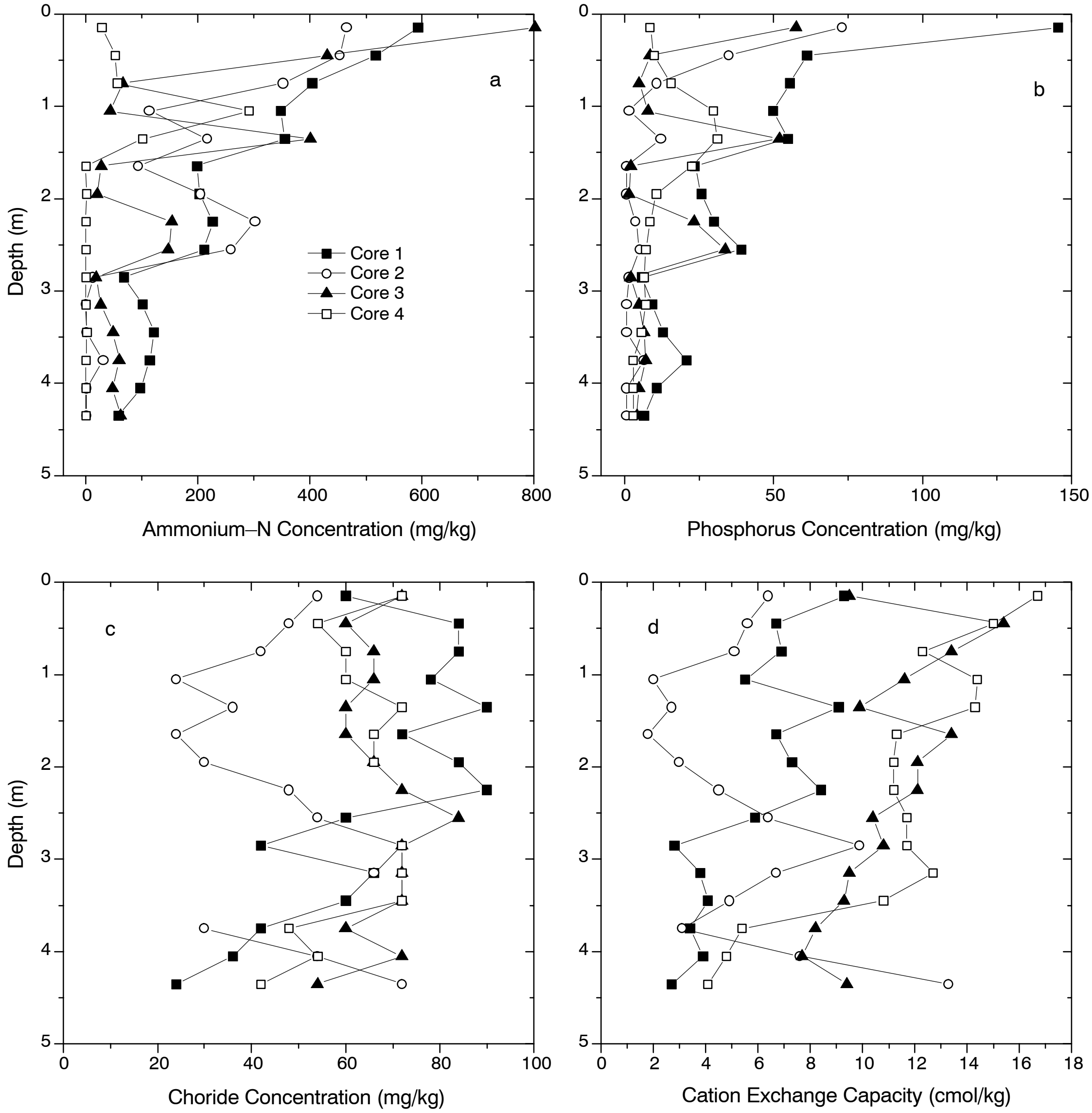

Figure 6. Profiles of (a) ammonium nitrogen, (b) phosphorus (Olsen–P), (c) chloride, and (d) cation exchange capacity at four different locations in the bottom of the 2.8–ha, 11–year–old cattle feedlot lagoon (same location as fig. 5a). Cores were collect along a transect at 30–m intervals.

- The rate of ammonium–N movement into the soil under lagoons ranged from 200 to 6000 kg ha^{-1} yr^{-1}, while chloride losses ranged from 500 to 8000 kg ha^{-1} yr^{-1}. Over the life of a lagoon (25 years), nitrogen accumulations beneath a 2.5–ha swine waste lagoon could exceed 2.3×10^5 kg.
- Ammonium–N and many other cations that seep from the lagoons are adsorbed by soil clays immediately beneath the compacted liner. In most cases, significant concentrations of ammonium–N did not accumulate to depths greater than 3 m. Organic nitrogen also is a significant form of nitrogen in the leachate and may contribute to environmental risk at some locations. Chloride and other anions penetrate to much lower depths (>4 m).
- The greatest risk of groundwater contamination from lagoons may occur after a facility is no longer in use. The large reservoir of ammonium and organic nitrogen beneath many lagoons could convert to nitrate and more readily move toward the water table.
- Clean up of lagoon sites may require some excavation and earthmoving. The cost of remediation should be considered at the time of lagoon design. It may prove more economically feasible to use a plastic liner to reduce the costs of clean up at closure. These analyses will be species and site dependent.

Acknowledgements

Technical assistance in the field and laboratory was provided by T. M. DeSutter. Analyses of various soil samples were provided by Hilary Kaiser while working in the laboratory of Charles Rice. Analysis of soil phosphorous was supplied by the laboratory of Gary Pierzynski. Gerard Kluitenberg assisted with the statistical analysis.

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