Seepage Evaluation of Older Swine Lagoons in North Carolina

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Abstract. *Thirty−four swine waste lagoon systems in North Carolina were examined for evidence of seepage losses to the shallow groundwater. All were constructed prior to the state's January 1993 adoption of stricter construction standards. Mineral nitrogen concentrations (ammoniacal plus nitrate nitrogen) were used as the primary indicators of seepage impacts. Total mineral concentrations were compared to the U.S. EPA drinking water standard for nitrate−N of 10 mg/L. The shallow groundwater on approximately one−third of the 34 systems met the EPA standard at a distance of 38 m (125 ft) downgradient from the lagoon(s).*

Keywords. *Groundwater, Lagoons, Seepage, Water quality.*

Swine production in North Carolina grew dramatically in the late 1980s and early 1990s, nearly quadrupling during that period. Virtually all of the growth involved intensive confinement systems that use wet waste handling and anaerobic lagoons. As of the beginning of 1993, state regulation required lagoon construction to meet the design standards recommended by the USDA Soil Conservation Service (SCS, changed in 1994 to Natural Resources Conservation Service, NRCS) in Appendix 10D of the *Agricultural Waste Management Field Handbook* (SCS, 1992). As of that date, well over 2000 swine waste lagoons were already in service in North Carolina (NCDENR, 1997). Many of those were sited and designed with NRCS assistance, but did not specifically include clay (or equivalent) liners as specified in the 1993 regulations.

Waste lagoons were expected to develop a seal at the liquid−soil interface that would impede seepage. Mechanisms for the phenomenon include physical clogging of pores by particulates or microbial gums and sludge (Chang et al., 1974; Barrington et al., 1987; Barrington and Madramootoo, 1989; Davis et al., 1973; Maulé et al., 2000). Many early studies concluded that the sealing effect would limit seepage to rates that would not significantly contaminate the shallow groundwater, even with sandy soils (e.g., Hills, 1976; Ritter et al., 1984; Miller et al., 1985; Rowsell et al., 1985). Some later studies found that self−sealing did not adequately control seepage on coarser materials (Ritter and Chirnside, 1990; Korom and Jeppson, 1994). Recent investigations of older, unlined lagoons in North Carolina found that about half of the lagoons studied had seepage losses high enough to exceed the drinking water standard for nitrate−nitrogen (Huffman and Westerman, 1995; Westerman et al., 1995). Those studies found that seepage problems were often localized, suggesting problems in construction where sandy lenses were not properly excavated and replaced with better materials. They reported concentrations of mineral nitrogen (nitrogen as both nitrate and ammonia) as high as 470 mg/L. Ham (2002) reported on ammonia and organic nitrogen distributions under lagoons in Kansas, showing concentrations in excess of 1000 mg/kg within the first meter and tapering off with depth. He attributed this to adsorption of the ammonia onto clays. In the stratified systems of the Atlantic Coastal Plain, where most North Carolina swine production is concentrated, nitrate from fertilizers and waste applications is very rarely observed below the first significant clay layer (Gilliam et al., 1996).

Concern for the environmental impacts of seepage have centered on excessive concentrations of nitrate−nitrogen in the groundwater. Although lagoon wastewater contains very little nitrate, the nitrogen present in seepage as ammonia, ammonium, or organic nitrogen can be converted to nitrate in the groundwater. The concern for possible groundwater contamination from lagoons prompted the North Carolina General Assembly to fund a large−scale survey of the older swine waste lagoons in the state. The survey was to extend the knowledge base by investigating a relatively large number of lagoons to see what contaminant concentrations were present in the shallow groundwater. The survey was to focus on systems built before the regulatory adoption of construction standards in 1993.

The primary objective of this survey was to determine the proportion of older (i.e., pre−1993) swine waste lagoons that pose a threat to local groundwater quality. A secondary objective was to determine whether soil textures of the upper profile (like those reported in soil surveys) could predict lagoon performance with respect to seepage losses.

Methods

The project was planned in consultation with the Groundwater Section of the Division of Water Quality of the North Carolina Department of Environment and Natural Resources. Since the focus was on systems that had been in operation for at least five years, it was assumed that seepage

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plumes within the area of interest would be well developed. It was therefore agreed that a one−time snapshot, as opposed to monitoring over some period of time, would be sufficient to indicate the presence and approximate severity of seepage contamination. Estimates of time and cost per site led to choosing a target of 40 sites. With the intent of providing a statistically valid sampling of lagoons within the state, a goal was set to identify 100 candidate sites from which 40 could be randomly selected.

Site Selection

Over 2600 letters were mailed to North Carolina swine producers to solicit cooperation in this project. To be included in the project, the lagoons had to predate 1993 and have reasonable access to a distance of at least 38 m (125 ft) from the lagoon to permit sampling operations. Only 136 responses were received. Fifty−two of those volunteered to cooperate in the study. Each of those sites was visited to assess its usability. The primary considerations were accessibility for sampling operations and absence of confounding factors such as mortality burial pits. Of the 52 sites, 22 had clear access, 8 had somewhat limited access, 9 had more limited access but could be used, 5 had very limited access, and 8 had no access. Limitations to access included buildings, fences, property boundaries, and woods.

In general, owners were not able to provide information regarding the specifics of lagoon construction, so it could not be determined whether the lagoons had clay liners. Common practice during that period did not include use of clay liners, so it is reasonable to assume that the construction materials were the soils on site.

The 40 candidate sites deemed most usable were scheduled for inclusion in the study. As the work progressed, some of those sites were lost for various reasons, such as changes in ownership. Two others were volunteered that had not responded to the original solicitation. The final number of sites included in the study was 36. Most of these sites were located in the Coastal Plain physiographic province of North Carolina. Three of the sites were in the Piedmont province. At each site, a topographic survey was conducted to determine the relative positions of the lagoons, buildings, nearby surface waters, and the general shape of the land.

Groundwater Sampling

Many of the sites had systems of two or more lagoons. For sites where the sampling procedure could not isolate a particular lagoon within a system, the lagoon complex was treated as a single unit. Where one or more of the lagoons on a site was constructed under the new regulations, the study focused only on the pre−1993 lagoon(s).

In North Carolina, standard permits for industrial waste sites define a review boundary at 38 m (125 ft) from a containment structure and a compliance boundary at 76 m (250 ft). Prior to 1993, lagoons were not individually permitted, but rather deemed “permitted by regulation” if the systems met the operational criteria in the North Carolina Administrative Code (NCAC, 2004). Although review and compliance boundaries were not defined under that arrangement, 38 m (125 ft) was selected, in consultation with the Groundwater Section, as a standard distance from the lagoons for groundwater sampling.

Three or more exploratory borings were made with 114 mm (4.5 in.) augers at approximately 38 m (125 ft) from

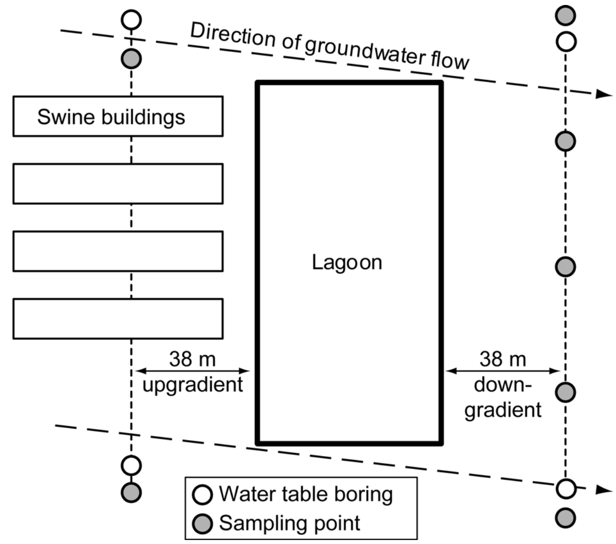

Figure 1. Layout of sampling points on a typical lagoon site.

the lagoon. Distances were measured from the interior top of the bank. The textures of cuttings were determined in the field, by feel, and recorded. Relative elevations of the water table in the boreholes were used to determine the most likely direction of groundwater flow. Once the direction of the local gradient was determined, sampling points were selected 38 m (125 ft) upgradient and 38 m (125 ft) downgradient of the lagoon. If the gradient was not well defined and the area was accessible, sample points were selected all around the lagoon(s). Buildings or other obstructions sometimes made it impossible to sample completely around the lagoons. In general, at least two sampling points were selected in upgradient positions, and four or more were selected in downgradient positions. Figure 1 shows a typical layout and how the points were chosen. Most systems were constructed on sloping land with the buildings situated upslope from the lagoon(s) to allow wastes to flow by gravity from the buildings into the lagoon(s). Since shallow groundwater generally flows in the direction of the surface slope, the gradients were usually similar to those shown in figure 1.

One of two methods was used for collecting groundwater samples, depending on the penetrability of the soils on the site. On most sites, it was possible to drive direct−push sampling probes (Diedrich Drill, Inc., La Porte, Ind.) into the

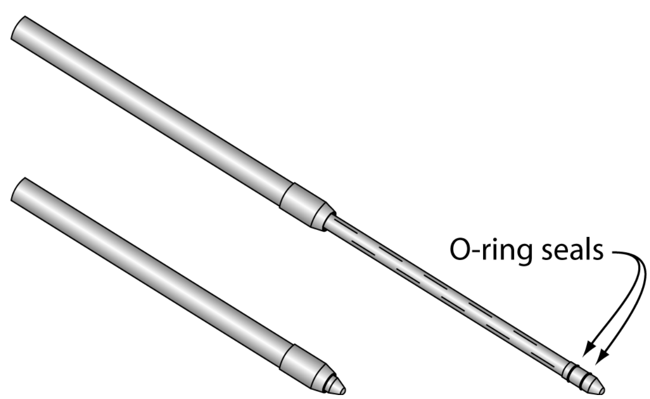

Figure 2. Direct−push tooling used for groundwater sampling. Top: slotted inner rod extended for water collection. Bottom: slotted inner rod retracted for driving to sampling depth.

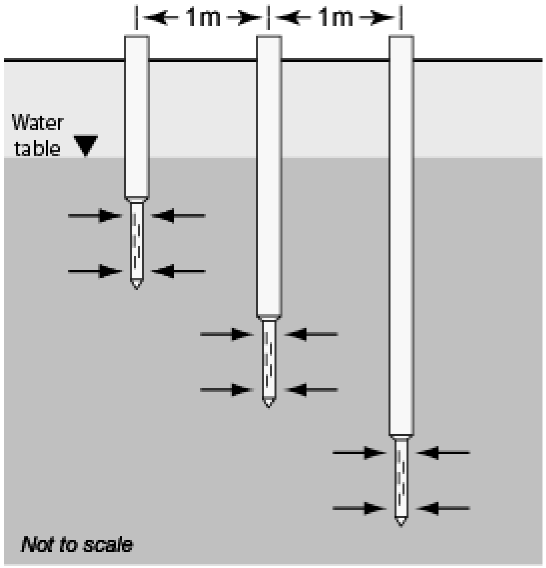

Figure 3. Profile sampling using direct−push tooling. Sample is bailed from slotted inner rod.

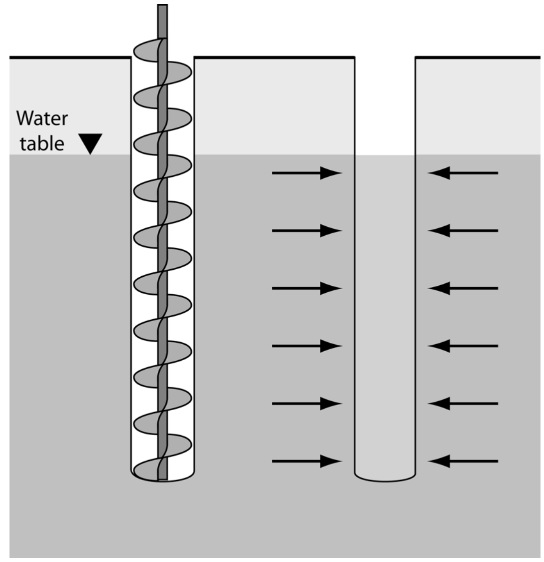

Figure 4. Auger−hole method for water sampling. Sample is bailed from open auger hole.

soil. The probes consist of a 51 mm (2.0 in.) diameter outer casing and a 29 mm (1.125 in.) diameter inner rod in 1.22 m (4 ft) sections, with drive points, shoes, and adapters. The probe assembly is illustrated in figure 2. Figure 3 illustrates sampling at multiple depths with the direct−push tooling. To avoid disturbance or interference between probes, multiple probes at one location were spaced approximately 1 m apart. The inner rod and outer casing were sealed together by two O−rings while the probe was driven to the desired depth. The inner rod was then pushed an additional 0.6 m (2 ft) to expose the slotted inner rod section. The slots were 51 mm (2.0 in.) long and 0.25 mm (0.010 in.) wide. A 250 mL sample was collected using a 12.7 mm (0.50 in.) diameter stainless steel bailer. The first flows into the sampler were collected for analysis. Tooling was cleaned between uses. The shallowest sample at a location was collected just below the water table. Additional samples were taken at 2.4 m (8.0 ft) intervals until either a restrictive layer was encountered or the capability of the drill rig was reached.

Table 1. Analytical methods.

	Method
TKN	Persulfate digestion and ammonia−salicylate method for automated analysis. Method 351.2 (EPA, 1979) with slight modifications including dialysis.
NH_3−N (ammonia)	Ammonia−salicylate method for automated analysis. Method 351.2 (EPA, 1979) or Standard Methods 418.F (APHA, 1981) with slight modifications including dialysis.
NO_3−N + NO_2−N (nitrate + nitrite nitrogen)	Cadmium reduction method for automated analysis. Method 353.2 (EPA, 1979), Technicon Industrial Method No. 100−70W (1973), or Standard Methods 418.F (APHA, 1981) with slight modification including dialysis.
Cl (chloride)	Ferricyanide method for automated analysis. Method 325.2 (EPA, 1979) or Standard Methods 407 D (APHA, 1981) with slight modifications including dialysis.
pH	Electrometric method. Method 150.1 (EPA, 1979) or Standard Methods 205 Conductivity (APHA, 1981).

The second method was used at eight sites because the resistance of the soil to the probes was so great that they could not be driven to the desired depths. In those cases, a hole was augered to about 1.5 m (5 ft) below the water table and a water sample was bailed from the open hole (fig. 4). This method limited sampling to only one sample for each location rather than the vertical profiles possible with the direct−push probes. Samples were collected as soon as there was sufficient water in the holes to permit bailing. Although it was less informative, sampling from auger holes was sufficient to indicate whether seepage was present in the shallow groundwater.

All samples were immediately placed on ice and delivered to the Environmental Analysis Laboratory in the Department of Biological and Agricultural Engineering at North Carolina State University. The analytical methods used are listed in table 1.

Seepage Classification

Anaerobic swine lagoons are strong sources of ammoniacal nitrogen. Most of the nitrogen present in the wastewater is in an ammoniacal form (NH_3 or NH_4^+). A minor fraction (typically about 20%) is in organic forms. Nitrate−N is not present in anaerobic lagoons in significant concentrations (Westerman et al., 1990; Barker et al., 2001). Where seepage rates were high, ammoniacal nitrogen was usually present in the shallow groundwater at concentrations well above the typical background concentrations, which are less than 1 mg/L (Spruill et al., 1996). Where ammoniacal nitrogen dominates, conditions are not conducive to complete conver−

Table 2. Classification criteria for evidence of seepage.

Class	Increase in Mineral−N Concentration from Upgradient to Downgradient Positions (mg/L)
None	<2
Weak	2−10
Moderate	10−40
Strong	40−100
Very strong	>100

Table 3. Operation/site characteristics and seepage summary for lagoon systems. Concentrations are sums of ammoniacal and nitrate nitrogen.

	Operation[a]			Lagoons		Adjacent Land Use[b]		Soil	Avg. Water Table		Upgradient Samples			Downgradient Samples			
Site	Type	Size (Mg)	Age (yr)	No.	Surface Area (ha)	Up−gradient	Down−gradient	Textures, 0−1.5 m	Depth (m)	Sample Method[c]	n[d]	Mean (mg/L)	Range (mg/L)	n[d]	Mean (mg/L)	Range (mg/L)	Seepage Class
1111	Fe−Fi	162	6	1	0.7	F	W	sc	2.1	P	3	2.1	0.1−3.4	8	10.0	1.0−22.6	Moderate
1116	We−Fe	71	7	1	0.2	W	W	fsl	1.8	P	6	0.0	0.0−0.1	5	0.1	0.0−0.3	None
1410	Fe−Fi	166	8	1	0.7	F	F	s, sl	2.1	P	4	3.6	0.1−13.7	9	62.2	4.2−253.8	V. Strong
1954	Fe−Fi	245	10	2	1.0	F	W	s	1.7	P	2	17.3	3.3−31.3	17	93.6	16.7−472.8	V. Strong
1961	Fe−Fi	228	7	2	1.1	F	W	sc	4.0	P	6	4.2	0.0−16.4	17	0.6	0.0−7.4	Weak
2757	Fe−Fi	365	15	1	0.3	F	W	sl	1.2	P	4	35.1	16.2−46.9	11	13.8	0.1−51.1	Moderate
3200	Fa−Fi	64	17	1	0.3	F	W	cl	5.0	A	2	11.1	10.4−11.7	7	29.6	7.7−80.0	Strong
3311	We−Fe	35	7	1	0.2	W&F	W	cl	1.6	P	3	1.1	0.4−1.6	4	3.7	0.2−13.8	Moderate
3373	Fe−Fi	150	6	1	0.9	W	F	c, cl	3.4	P	3	0.5	0.0−1.2	12	4.6	0.0−13.3	Moderate
3914	Fe−Fi	180	6	1	0.7	F	F	sl	1.7	P	3	9.4	2.2−15	9	11.7	0.5−32.8	Moderate
3933	Fe−Fi	566	7	1	0.7	F	F	sc	5.9	A	2	20.0	9.2−30.8	5	116.8	3.3−332.0	V. Strong
4444	Fe−Fi	187	20	2	0.3	W	F	cl, scl	1.8	P	1	2.9	−−	9	1.8	0.6−3.7	None
4547	Fe−Fi	1669	24	2	1.4	F	F	scl	2.0	P	4	10.5	5.9−13.8	13	58.6	0.5−182.1	V. Strong
4551	We−Fe	36	6	1	0.2	W&F	F	ls	1.9	P	3	7.3	4.0−9.7	7	74.1	0.4−391	V. Strong
4589	Fe−Fi	103	20	3	0.5	F	F	sl	2.5	P	2	17.8	14.6−21.1	9	29.6	0.3−129.1	V. Strong
4649	Fe−Fi	76	14	1	0.5	F	F	scl	1.8	P	5	9.1	2.5−26.8	15	26.2	0.1−79.1	Strong
4777	Fe−Fi	225	29	2	1.0	W	W	cl, scl	1.5	P	2	0.1	0.0−0.3	5	0.2	0.0−0.5	None
5437	We−Fe	35	8	1	0.3	W	F	s, ls	1.2	P	3	0.6	0.2−0.9	10	12.0	0.1−33.4	Moderate
5555	Fa−Fi	193	23	2	0.2	F	W	cl, sl	1.9	A	1	0.6	−−	4	15.0	8.7−20.7	Moderate
5827	Fe−Fi	270	6	2	1.1	W&F	F	cl	0.9	P	2	10.3	7.9−12.8	21	29.4	5.5−79.9	Strong
6603	Fe−Fi	255	11	4	2.0	F	F	sl	3.2	P	5	9.9	0.5−25.1	7	19.3	2.2−55.1	Strong
6633	We−Fe	35	7	1	0.2	F	W	sicl	2.0	P	2	1.0	0.2−1.8	5	0.5	0.1−1.7	None
6653	Fa−We	236	6	1	0.9	F	F	l, cl	4.2	P	2	5.3	2.8−7.7	12	37.1	4.3−329.1	V. Strong
6726	Fe−Fi	92	6	2	0.3	W	W	ls	1.8	P	2	0.8	0.8−0.9	4	86.2	32.0−232	V. Strong
7144	Fa−We	192	20	1	0.5	F	F	cl	2.8	P	2	3.1	2.9−3.4	10	11.9	0.3−24.7	Moderate
7225	Fe−Fi	22	19	2	0.4	F	F	ls	1.2	P	14	2.8	0.2−19.5	11	53.3	3.2−279.0	V. Strong
7286	Fe−Fi	294	7	1	1.1	F	W	cl	1.1	P	2	4.3	1.9−6.7	12	10.0	0.2−44.3	Strong
7674	Fa−Fi	76	7	1	0.5	W&F	F	sic	7.7	A	1	4.8	−−	3	1.3	0.0−3.3	None
7777	Fa−We	189	na[e]	1	0.9	W&F	W	cl	2.2	A	1	2.9	−−	5	3.3	0.9−7.7	Weak
7940	We−Fe	393	8	2	2.1	F	W&F	sc, cl, c	1.6	A	5	7.8	0.2−14.7	8	18.8	0.1−68.9	Strong
8158	Fe−Fi	35	7	1	0.3	W	F	l, c	1.2	P	4	0.4	0.3−0.6	16	5.3	0.2−35.8	Moderate
8829	Fa− Fe	721	10	1	0.9	W&F	F	sic, cl, c	2.1	A	1	1.2	−−	7	17.1	10.4−28.6	Moderate
8971	Fa− We	250	7	2	1.2	F	F	scl	1.7	P	4	19.1	6.3−37.0	8	20.2	0.7−89.9	Strong
9087	Fa−Fi	153	9	2	1.3	F	W	sl, c	5.6	A	2	9.1	6.7−11.5	5	6.1	1.5−17.5	Moderate

[a] Fa = farrow; We = wean; Fe = feeder; Fi = finish. “Size” refers to design steady−state live weight. Source: NCDENR (1997).
[b] W = woods, F = fields, and W&F = mixture of woods and fields.
[c] P = direct push probe, and A = auger.
[d] n = number of samples analyzed from a site−location combination.
[e] Estimated at 15 years.

sion to nitrate (NO_3^-). This is probably due to a combination of high seepage and limited oxygen availability in the saturated sediments. High ammonia concentrations may also be toxic to nitrifying bacteria (Westerman et al., 1995). Where nitrate is the dominant form, the oxygen supply is sufficient to permit nitrification of the ammoniacal nitrogen in the seepage.

Assessments of seepage were based on the sum of ammoniacal nitrogen and nitrate nitrogen concentrations. These two forms represent the major forms of mineral nitrogen present in the groundwater. Samples were also analyzed for total Kjeldahl nitrogen (TKN), which represents the sum of ammoniacal nitrogen and organic nitrogen. In anaerobic decomposition, such as occurs in lagoons, organic nitrogen is converted to ammoniacal nitrogen. In the presence of sufficient oxygen, ammoniacal nitrogen can be converted to nitrate nitrogen, which is the form that is most mobile in groundwater. Concentrations of either mineral form of nitrogen in natural groundwater are typically less than 1 mg/L. Most of the mineral nitrogen applied to agricultural fields, whether by manure, wastewater, or commercial fertilizers, appears in the nitrate form after a short period of time. Concentrations of 5 to 15 mg/L nitrate−N are common in the shallow groundwater under agricultural fields (Krider, 1986). Chloride (Cl^-) concentration is sometimes used as a seepage indicator (Ritter et al., 1984; Westerman et al., 1995; Ham, 2002) and was also evaluated. Since the chloride−based indications were very similar to the nitrogen−based indications, only the nitrogen−based results are presented here.

The U.S. Environmental Protection Agency’s drinking water standard for nitrate−N is 10 mg/L. There is no standard for ammoniacal nitrogen, but since it is readily converted to nitrate−N under favorable conditions, it was included with nitrate−N in these assessments.

Each site rating was based on the difference between the minimum upgradient concentration and the maximum downgradient concentration of mineral−N. This method gives the most severe rating because it does not average in samples that may have been taken above, below, or to the side of a seepage plume. Concentration differences were used to isolate the nitrogen contributed by lagoon systems from nitrogen contributed by upgradient sources, such as agricultural fields. The concentration ranges for the various classes for seepage evidence are given in table 2.

RESULTS

The goal of randomly selecting 40 study sites from a large pool of candidates could not be met because the number of volunteered sites was too small. However, the 36 sites included in the study provide a reasonable representation of the types of conditions and performance of older lagoons in the state. The conditions and performance observed in this study were very similar to those found in earlier work (Huffman and Westerman, 1995; Westerman et al., 1995).

Shallow rock was encountered at two of the 36 sites, both of which were located in the Piedmont. Attempts to drill into the rock with the available equipment were unsuccessful. Since groundwater samples could not be collected, it was not possible to assess the seepage characteristics of those lagoons. Seepage assessments were therefore completed on only 34 sites.

Table 3 presents physical and operational characteristics of the sites, along with the results of the groundwater analyses. For each of the 34 sites, the means and ranges of mineral nitrogen concentrations are shown for both upgradient and downgradient locations. On 16 sites, the maximum upgradient nitrogen concentration exceeded 10 mg/L. One of those had a mixture of woods and fields upgradient. The remaining 15 had agricultural fields upgradient.

A statistical analysis of the results shown in table 3, using the maximum difference between upgradient and downgradient mineral nitrogen concentrations as the response variable, did not find any significant predictors among the variables Type of Operation, Size of Operation, Age of Operation, Lagoon Surface Area, or Average Water Table Depth.

The seepage classes at 38 m (125 ft) downgradient are summarized in table 4. Seven of 34 sites (21%) ranked as None or Weak. Eleven of 34 (32%) ranked as Moderate. Sixteen of 34 (47%) ranked as Strong or Very Strong.

County soil surveys provide descriptions of the upper 1.5 to 2.4 m (5 to 8 ft) of the soil profile. It would be useful if the appropriateness of a site for lagoon construction could be predicted on the basis of the soil type. To examine the relationship between soil texture and seepage classes, textures in the upper 1.5 m (5 ft) of the soil profile and seepage classes at 38 m (125 ft) downgradient were compared, as presented in table 5. As can be seen from the wide ranges of textures in the various classes, the textures in the upper 1.5 m of the soil profile do not provide a good indication of seepage containment.

Table 4. Summary of seepage classes at 38 m (125 ft).

Seepage Class	Number of Lagoons	Percent
None	5	15
Weak	2	6
Moderate	11	32
Strong	7	21
Very Strong	9	26
Total	34	100

DISCUSSION

Sites ranked as either None or Weak were judged very unlikely to present any contamination problem. They contributed less than 10 mg/L mineral−N to the shallow groundwater. Sites ranked Moderate or higher could present problems if the shallow groundwater was extracted for use.

While sites ranked Moderate or higher would not meet EPA drinking water standards, they do not necessarily require corrective action. All of the lagoons in this survey were positioned on the landscape such that the seepage plumes moved toward areas where direct use of the shallow groundwater was very unlikely. Many are positioned immediately upgradient from woodlands or swamps that can assimilate modest nutrient loads. In some cases, there were streams nearby where the plumes would discharge with the natural flow of the shallow groundwater and be greatly diluted. Before requiring remedial action, consideration should be given to the affected area and whether adverse impacts actually exist. In a case where seepage losses are excessive and the plume has an actual adverse impact, corrective action should be taken. If a plume does not have an actual adverse impact at present, but the owner can foresee the possibility of future problems, corrective action would be prudent.

While inspection of tables 3 and 5 suggests a general trend toward higher mineral nitrogen concentrations on sites where sandy soils (s, sl, ls) were observed (1410, 1954, 4551, 4589, 6726, and 7225), there were lagoon systems on locations with sandy soils (fsl, sl) that showed little evidence of seepage (1116, 2757, and 3914). Conversely, some systems on locations with clayey soils (scl, cl, sc, c) had strong indications of seepage (3200, 3933, 4547, 4649, 5827, 7286, 7940, and 8971). The weakness of the relationship between seepage performance and textures in the upper profile can be explained in part by the fact that lagoons were often constructed in and with soil materials that were deeper than those that would be described in soil surveys. Clayey horizons that typically underlay sandy surface horizons in the Coastal Plain could have been used in lagoon construction. Soil textures may also vary dramatically, both vertically and horizontally, within the range of distances that are typical of lagoon dimensions.

On some sites, high concentrations were observed across much of the downgradient area, giving evidence of a broad plume. On other sites, high concentrations were found in only a few samples, suggesting a narrow plume that may have been the result of transport through sandy lenses that were not properly excavated and patched during lagoon construction.

Table 5. Soil textures observed in upper 1.5 m (5 ft) on sites in each seepage class.

Seepage Class	Soil Textures in Upper 1.5 m of the Soil Profile
None	Fine sandy loam, sandy clay loam, clay loam, silty clay loam, silty clay.
Weak	Sandy clay, clay loam.
Moderate	Sand, loamy sand, sandy loam, loam, clay loam, sandy clay, silty clay, clay.
Strong	Sandy loam, sandy clay loam, clay loam, sandy clay, clay.
Very strong	Sand, loamy sand, sandy loam, loam, sandy clay loam, clay loam, sandy clay.

Detailed reports for all sites, including site layout, sample locations, and analytical results, are in Huffman (1999).

CONCLUSIONS

Approximately one−fifth of pre−1993 swine waste lagoon systems in this survey contributed less than 10 mg/L mineral−N to the shallow groundwater at a distance of 38 m (125 ft) downgradient from the lagoons. Although four−fifths of the systems showed heavier loadings to the shallow groundwater, none of the systems in this survey were positioned in the landscape such that the seepage plumes represented an immediate hazard to groundwater users.

Lagoons constructed on sites with coarse−textured soils were expected to have higher seepage losses than those constructed on sites with fine−textured soils. Although the data suggest a very weak correlation between soil texture in the upper 1.5 m and seepage losses, soil textures in the upper 1.5 m of the profile were not good predictors of lagoon seepage performance.

A follow−up study was initiated to examine the variability of plume strength with distance from the source. It will be reported in a later article.

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