SEEPAGE FROM EARTHEN ANIMAL WASTE PONDS AND LAGOONS— AN OVERVIEW OF RESEARCH RESULTS AND STATE REGULATIONS

D. B. Parker, D. D. Schulte, D. E. Eisenhauer

ABSTRACT. *Wastewater seepage from earthen animal waste lagoons and storage ponds can contaminate groundwater with nutrients and pathogens. For almost 30 years, the subject has been the focus of laboratory and field research projects designed to (1) measure if and how much earthen ponds and lagoons leak, (2) determine how different soil types affect seepage rates, and (3) evaluate the magnitudes and mechanisms of sealing from animal waste. In this article we present a research review performed to determine how researchers have attempted to answer these questions and how well they have been answered. We discuss weaknesses in the body of knowledge and present further research and educational needs. We also performed a review of 14 state regulations to assess and compare how different states govern seepage from ponds and lagoons. Six states regulate the maximum allowable seepage rate from ponds and lagoons (values ranging from 0.042 to 0.63 cm/day) while another six states regulate the maximum hydraulic conductivity of earthen liners (values ranging from 0.086 to 0.0086 cm/day). The two remaining states regulate neither. The results of this research and regulatory review demonstrate that there is still much to be learned about seepage from animal waste ponds and lagoons. We suggest that a risk-based approach to regulating seepage may be appropriate in the future.*

Keywords. *Seepage, Infiltration, Pond, Lagoon, Animal waste, Manure, Regulations, Water quality.*

In the past decade, public and regulatory awareness on environmental aspects of agricultural practices has increased. Because of the potential for groundwater contamination, a number of research projects have focused on seepage from wastewater lagoons and storage ponds at concentrated animal feeding operations (CAFOs). Many states have promulgated regulations to minimize the risks of groundwater contamination at CAFOs.

The objectives of this review were to (1) summarize previous research performed in the area of seepage from animal waste lagoons and storage ponds, (2) discuss primary questions answered by the research and address questions left unanswered, (3) evaluate and compare current state regulations governing the design and construction of animal waste lagoons and storage ponds, and (4) present some future research and educational needs in this subject area.

RESEARCH REVIEW

There are three primary questions which researchers have attempted to answer related to seepage from animal waste ponds and lagoons in the past 30 years:

- Do earthen animal waste ponds and lagoons leak, and if so how much do they leak?
- How does soil type affect seepage rates and hydraulic conductivities?
- Does animal waste cause a sealing effect with time, and what is the magnitude and the mechanism of sealing?

To evaluate how researchers have answered these questions, we performed a literature review of the Agricola and Uncover library databases, bibliographies, and publication references. Previous literature reviews and compilations (Reese and Loudon, 1983; Sweeten, 1992; Moffitt et al., 1993) were also used to identify and locate previous research projects. For this review, research projects were categorized into full-scale field seepage measurements, groundwater monitoring field studies, soil field studies, and small-scale laboratory studies. Each reference was reviewed individually to obtain the summaries and conclusions that follow.

FULL-SCALE SEEPAGE INVESTIGATIONS

Full-scale studies are performed in the field on "full-size" ponds and lagoons, as compared to pilot scale or "small-scale" studies which are performed in a laboratory type setting. Most full-scale studies consisted of determining estimated seepage losses using a water balance approach, where pond water levels are monitored, then estimated evaporation rates are subtracted to obtain estimated seepage loss.

Davis et al. (1973) measured infiltration rates in a newly constructed liquid manure waste basin system on a dairy farm. Twenty-cm diameter cylinders were installed on the floor of the basins. First, seepage of fresh water was measured; then seepage of wastewater was measured. Seepage rates of 120 cm/day were measured when using

---

Article was submitted for publication in May 1998; reviewed and approved for publication by the Structures & Environment Division of ASAE in January 1999.

The authors are **David B. Parker, Ph.D., P.E.,** ***ASAE Member Engineer,*** Agricultural Engineer and Assistant Professor, West Texas A&M University, Division of Agriculture, Canyon, Tex., **Dennis D. Schulte, Ph.D., P.E.,** and **Dean E. Eisenhauer, Ph.D., P.E.,** ***ASAE Member Engineers,*** Professors, University of Nebraska, Dept. of Biological Systems Engineering, Lincoln, Nebr. **Corresponding author:** Dr. David B. Parker, West Texas A&M University, Box 60998, Canyon, TX 79016; voice: (806) 651-2563; fax: (806) 651-2504; e-mail: dparker@wtamu.edu.

Transactions of the ASAE

VOL. 42(2): 485-493

fresh water. When using dairy wastewater, measured seepage rates decreased from 6 cm/day after two weeks to 0.5 cm/day after four months. Davis concluded that dairy waste ponds were "effectively self-sealing".

Robinson (1973) measured seepage from an existing beef cattle storage pond in California. The pond was cleaned with a backhoe prior to the experiments. Seepage rates were measured by monitoring wastewater level fluctuations in the pond and correcting for evaporation, which was assumed to be 70% of pan evaporation. The seepage rate was 11 cm/day initially, then 0.6 cm/day after three months and 0.3 cm/day after six months.

Demmy et al. (1993) designed and constructed a floating evaporation pan for measuring evaporation from a dairy basin in Florida. Seepage was estimated by mass balance. They reported an average evaporation rate of 0.052 cm/day and an average seepage rate of 2.25 cm/day. Their measurements were made over time intervals of 22 to 118 min. Experimental data and calculated infiltration rates for the research from full-scale studies is summarized in table 1.

GROUNDWATER MONITORING INVESTIGATIONS

Measurement of groundwater quality is a common method used to evaluate effects of leakage from lagoons and ponds. Nordstedt et al. (1971) monitored groundwater quality adjacent to a three-stage lagoon system constructed for a commercial dairy farm. Monitoring wells were installed to depths of 2.43.0 m below the ground surface at distances of 4.6, 15.2, and 30.5 m from an anaerobic lagoon and an aerobic lagoon. Groundwater depths ranged from 0.3 to 1.2 m. Results of groundwater sampling for BOD, salts, and nitrate-Nitrogen (nitrate-N) during the first eight months of operation indicated some seepage near the lagoons.

Sewell (1978) evaluated the effects of a newly constructed dairy lagoon system on nearby groundwater quality. Seven monitoring wells with an average depth of 3.4 m were installed in the vicinity of the lagoon. Groundwater samples were collected monthly for three years. Nitrate-N concentrations were elevated immediately after loading, but decreased at a rate of 0.09 mg/L per week. After six months, nitrate-N levels decreased to near preloading conditions. The author credited the decrease in contaminant concentrations in groundwater to the development of sealing in the lagoon.

Ciravolo et al. (1979) investigated the effect of three anaerobic swine waste lagoons on groundwater quality in the Atlantic Coastal Plain Region. All three lagoons were located in areas where shallow groundwater existed. Monitoring wells were installed at distances ranging from 6 to 37 m from the lagoons. Groundwater sampling indicated that wastewater entered groundwater from all three lagoons. Contaminant levels were much higher in the lagoon located in a coarse soil, as compared to the lagoons located in a sandy loam. Instances where contaminant concentrations were greater further from the lagoons were attributed to contamination from lagoon overflow. They suggested that rupture of lagoon seals may be a function of: (1) drying of exposed soils on embankments when lagoon levels drop; and (2) gas release from microbial activity in soil beneath the seal. They also suggested that overflow may pose a greater threat to water systems than seepage.

Hegg et al. (1979) monitored groundwater quality at three newly constructed anaerobic swine lagoons in South Carolina for two years. Shallow monitoring wells were installed around the lagoons. Concentrations varied widely, with only a few wells showing definite contamination. The authors concluded that leakage from the lagoons occurred at specific locations where sealing of the lagoon did not occur. A water balance suggested a leakage rate of 0.034 cm/day. Results from monitoring wells were variable and could not be used to conclude that leakage was occurring. The authors stated that a larger number of monitoring wells would be required to characterize the site accurately.

Phillips et al. (1983) installed porous ceramic cup samplers below and adjacent to two newly constructed dairy manure storage basins in Ontario. Soils at both basins consisted of clay. The groundwater at both sites was very

Table 1. Daily water loss and elapsed time since start of infiltration from full-scale seepage studies

Author	Location & Waste Type	Groundwater Conditions	Soil Conditions	Measured Water Loss (cm/day)	Estimated or Measured evap. (cm/day)	Calculated Seepage Rate (cm/day)
Robinson (1973)	California (Cattle)	Groundwater at 1.7 m	Layered clay to clay loam, sand layer at 1.7 m	11.20 (0 d)*† 1.16 (90 d) 0.51 (180 d)	0.60 (90 d) 0.21 (180 d)	0.56 (90 d) 0.30 (180 d)
Davis et al. (1973)	California (Dairy, newly constructed)	NA	Sandy loam	120 (0 d)† 5.8 (14 d) 0.51 (120 d)	0.66 (0 d) 0.43 (14 d) 0.25 (120 d)	119.3 (0 d) 5.37 (14 d) 0.26 (120 d)
Hegg et al. (1979)	S. Carolina (Swine, newly constructed)	0.3 m below pond surface	NA	NA	NA	0.034 (463 d)‡
Demmy et al. (1993)	Florida (Dairy, established)	3-6 m below ground level	NA	NA	0.052	2.25 (4 h)
Parker (1995)	Nebraska (Beef, established)	30 m below ground level	Silt loam and clay loam	1.47	0.60	0.87 (22-yr-old pond)

* Numbers in parentheses reflect elapsed time in days since start of infiltration.
† For fresh water.
‡ Average over 463-day monitoring period.
NA = data not available.

shallow, and was above the bottoms of both basins during most of the three-year monitoring period. Nutrient concentrations in groundwater samples showed elevated concentrations of phosphorus and ammonium, and indicated that some leakage was taking place.

Ritter et al. (1984) monitored groundwater quality near an unlined two-stage anaerobic swine lagoon in Delaware for four years. Twelve monitoring wells were installed around the two lagoons. Soils varied from sandy loam to loamy sand with groundwater 2 m below ground level. Nitrate, ammonium, and chloride concentrations increased considerably after initial loading of the lagoons, then decreased with time.

Miller et al. (1985) installed groundwater sampling wells and porous cups beneath and around a newly constructed earthen lagoon at a beef cattle operation in Ontario. Soils consisted of coarse sand with occasional gravel layers, with groundwater located 12 m below the pond bottom. Neutron probe tubes were installed within the lagoon. Sampling results indicated a rapid infiltration rate when manure was first added, but the rate declined after about eight weeks. The authors concluded that the lagoon became effectively sealed within 12 weeks of manure addition, and that, with some limitations, unlined earthen lagoons were environmentally acceptable even in sandy material.

Westerman et al. (1995) monitored groundwater quality near two newly constructed anaerobic swine lagoons located in an area with very shallow groundwater conditions. The soils consisted of 5 to 12 m of sand underlain by clay layers. Sixteen monitoring wells were installed around the first lagoon, and 12 were installed around the second. Elevated concentrations of several parameters, including ammonium and chloride, provided evidence that seepage occurred throughout the five-year monitoring period.

Subsurface Soil Investigations at Existing Waste Sites

Miller et al. (1976) sampled soil beneath four hog manure lagoons. Two lagoons were in clayey soils and had been in use for two years. The other two were in loamy soils and had been in use for 810 years. In the clayey soils, ammonium levels were elevated in the top 2030 cm, then quickly decreased to background levels with depth. In the loamy soils, ammonium concentrations were elevated to the maximum sampled depth of 420 cm. Nitrate levels were low beneath all lagoons. Their results showed that seepage was greater in the coarser soils. However, since the lagoons located in the clayey soils were in use for a shorter time, they stated that definitive conclusions could not be made.

Clark (1975) evaluated seepage from naturally occurring playa lakes in Texas. He found evidence of seepage based on elevated chloride concentrations in subsurface soil samples. Nitrate concentrations were minimal below a 1 m depth. Clark concluded that there was “little hazard to groundwater from feedyard runoff caught in playa lakes”.

Smith et al. (1993) evaluated seepage from playa lakes used for storing feedlot runoff in the Texas panhandle area. Soil borings were drilled to a maximum depth of 15 m. They found no indication of leaching of nitrate, ammonium, organic nitrogen or phosphorus below 1.5 m. Smith stated that the rim around the playa was more permeable than the center of the playa.

Parker et al. (1999) investigated water and chemical transport beneath a 22-year-old beef feedlot storage pond in Nebraska. Soil samples were collected from 14 borings to a depth of 6.1 m. A seepage rate of 0.87 cm/day was measured after a large storm event, following a period of time when the pond was empty. Nitrate was not found beneath the pond bottom, but isolated areas of nitrate were found beneath the pond sidewalls. Potassium, chloride, ammonium, and organic nitrogen concentrations were elevated to the maximum depth explored, indicating that seepage had occurred from the pond.

Small-scale Laboratory Studies

Chang et al. (1974) performed a study in which twenty-five soil columns of four soil types were placed at the bottom of a newly constructed basin in California. Columns were recovered 3, 7, 17, 29, and 64 days after filling with wastewater, and hydraulic conductivities were measured by the constant head method. Due to limitations in the constant head method, hydraulic conductivities could not be measured after 17 days.

Hills (1976) simulated 12 anaerobic lagoons using 166-L drums in New Zealand. The simulated lagoons varied in depth from 2.5 to 4.5 m with a diameter of 0.6 m. Variables for the study included basin depth (2, 3, and 4 m), soil type (loam, silt loam, sand loam, and clay loam) and soil thickness (15, 25, and 35 cm). The lagoons were initially filled with clean water, followed by varying concentrations of dairy waste. All of the lagoons showed sharp reductions in permeability after filling with dairy waste, and after three months all of the lagoons had similar final infiltration rates.

DeTar (1979) measured infiltration of dairy waste into four different soils using basin and double-ring infiltrometers in Pennsylvania. Various manure water dilutions were used in the experiments. Infiltration rates decreased with increasing solids concentrations but results were erratic at low total solids concentrations. Infiltration rates followed a diurnal oscillating pattern, decreasing during the heat of the day when air temperatures were high and increasing in the evening hours when air temperatures were cooler. The authors could not explain the mechanism and apparent relationship to temperature, as wastewater temperatures were not recorded.

Culley and Phillips (1982) measured hydraulic conductivities in columns of three soil types in Ontario. Hydraulic conductivity measurements were made using fresh water and cattle wastewater containing about 3% solids. The rate of sealing was greater for sand than for finer soils. The authors stated that the texture of the soil material selected for the liner may have little impact on the extent of groundwater contamination.

Barrington and Jutras (1983) performed laboratory infiltration measurements on nine soil cores of various textures in Quebec. Infiltration rates were measured for both fresh water and dairy wastewater. Final hydraulic conductivities were similar for all soil types, and the authors indicated that the sealing effects were a function of soil particle size distribution rather than initial hydraulic conductivity. No correlation was found between soil texture and infiltration.

Phillips et al. (1983) constructed earthen storage basins at three sites with different soil types. The small basins, 4.5 × 4.5 × 1.5 m deep, were filled with dairy wastewater. Piezometers were installed to monitor groundwater movement. Water samples were collected beneath the basins using ceramic cup samplers. Phosphorus concentrations in groundwater were elevated in all three soils; whereas, nitrate was elevated only in the sandy soil.

Rowsell et al. (1985) performed a laboratory study to determine sealing effects on a sandy loam, loam, and clay soil in Ontario. Beef manure was applied to soil columns of 11.0-cm length. Infiltration rates decreased rapidly with time. They concluded that the decrease in infiltration was due to physical blocking and not chemical or biological characteristics.

Barrington and Madramootoo (1989) performed a laboratory investigation to study seal formation during infiltration of swine wastewater into a sand and a clay loam in Quebec. Piezometers were installed at different points in the 14.0 cm diameter × 20.0 cm long soil columns to measure heads and differentiate between hydraulic conductivities developed in the surface mat, the soil-mat interface, and the soil. Results showed that, for sand, a sealing layer developed within the surface manure mat and sometimes at the manure soil interface, while for clay loam sealing occurred at the surface manure mat, the manure soil interface, and within the surface 10-cm depth of the soil core. A summary of experimental data, infiltration rates, and hydraulic conductivities for the research from small-scale laboratory studies is presented in table 2.

DISCUSSION OF RESEARCH REVIEW

Based on results of field seepage measurements and groundwater and soil sampling studies, it is evident that seepage can occur from earthen ponds and lagoons installed without any precautionary measures to minimize seepage. As summarized in table 1, the magnitude of the seepage rates can be quite variable.

In individual experiments, researchers had some success in determining how soil type affects seepage, and generally found that fine-grained soils had lower seepage rates and hydraulic conductivities than coarse-grained soils. The more important question, however, is whether these results can be applied universally to all soil types, or whether they are valid only on a site-specific basis. To answer this question, selected infiltration rates from all of the experimental results presented herein were plotted as a function of time since wastewater was placed in the lagoon or holding pond (fig. 1). Rather than plotting every data point, values were selected from each manuscript with the purpose of presenting the full range of values, and for this reason regression analyses of the data is not presented. The data were grouped into three soil types: (1) sand, (2) loam and sandy loam, and (3) clay and clay loam. When examining all of the data together, it is apparent that infiltration rate decreases with time due to some type of

Table 2. Daily infiltration rate, hydraulic conductivity, and elapsed time from small-scale laboratory studies

Author	Location &Waste Type	Type of Experiment	Soil Types	Infiltration Rate for Infiltrate (cm/day) at Time Period Denoted	Hydraulic Conductivity for Waste Water (cm/day) at Time Period Denoted	Hydraulic Conductivity for Fresh Water (cm/day) at Time Period Denoted
Chang et al. (1974)	Calif. (Dairy)	Soil columns 5.1 cm diameter × 30.5 cm long planted in bottom of newly constructed pond	Silica sand	14.4 (64 d)*	3.6 (64 d)	343 (0 d)
			Sandy soil	0.72 (17 d)	0.18 (17 d)	53.8 (0 d)
			Loamy soil	0.60 (17 d)	0.15 (17 d)	16.8 (0 d)
			Silty clay soil	3.6 (7 d)	0.91 (7 d)	5.8 (0 d)
Hills (1976)	New Zealand (Dairy)	Twelve small-scale lagoons constructed from 16-L drums	Sand loam	0.090 (270 d)	0.0075 (270 d)	0.059 (35 d)
			Loam	0.055-0.088 (270 d)	0.0043-0.0069 (270 d)	0.012-0.020 (35 d)
			Silt loam	0.095 (270 d)	0.0077 (270 d)	0.056 (35 d)
			Clay loam	0.024 (270 d)	0.0020 (270 d)	0.0036 (35 d)
DeTar (1979)	Pennsyl. (Dairy)	Measured infiltration using basin and double-ring infiltrometers at various solids contents	Shaley clay	0.14-0.50 (7 d)		
			Sandy loam	0.14-1.03 (7 d)		
			Clay	0.22-1.18 (7 d)		
			Clay	0.12 (12 d)		
			Gravelly sandy loam	0.24-0.48 (15 d)		
Culley & Phillips (1982)	Ontario (Beef)	Measured infiltration with 7.6 cm dia. × 7.6 cm long soil cores with constant head permeameter	Sand	0.06 (10 d)	0.15 (10 d)	1470 (0 d)
			Loam	0.04 (10 d)	0.13 (10 d)	270 (0 d)
			Clay	0.04 (10 d)	0.13 (10 d)	410 (0 d)
Barrington & Jutras (1983)	Quebec (Dairy)	Measured infiltration on 9 soil cores of various textures	Sand (2 types)	0.043-0.057 (35 d)	0.0025-0.0033 (35 d)	182-203 (0 d)
			Loam (3 types)	0.052-0.060 (35 d)	0.0030-0.0035 (35 d)	196-1953 (0 d)
			Clay Loam (1 type)	0.057 (35 d)	0.0033 (35 d)	---
			Clay (3 types)	0.019-0.056 (35 d)	0.0011-0.0033 (35 d)	0.013-183.5 (0 d)
Rowsell et al. (1985)	Ontario (Beef)	Measured infiltration on 110 mm long soil cores	Sandy loam	0.095-0.13 (30 d)	0.010-0.013 (30 d)	
			Loam	0.086-0.13 (30 d)	0.0095-0.015 (30 d)	
			Clay	0.035-0.0054 (30 d)	0.0038-0.0059 (30 d)	
Barrington & Madramootoo (1989)	Quebec (Swine)	Measured infiltration and differential pressures across 140 mm dia. × 200 mm soil columns	Sand	0.26-0.36 (69 d)	0.13-0.18 (69 d)	829 (0 d)
			Clay loam	0.15-0.27 (69 d)	0.075-0.13 (69 d)	763 (0 d)

* Numbers in parentheses reflect elapsed time in days since start of infiltration.

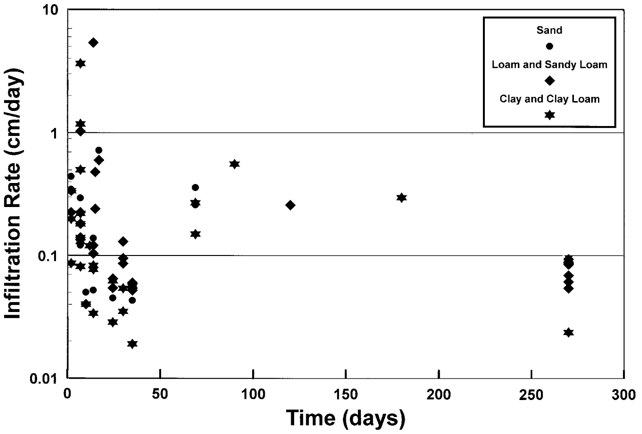

Figure 1–A comparison of published infiltration rates. The time denoted is the elapsed time since wastewater was placed in the earthen-lined structure in each of the experiments.

sealing process (fig. 1). When the three soil types are examined individually, however, the trends are not as distinct. The results of this analysis suggests that there may be problems with accurately predicting infiltration rate or hydraulic conductivity based on soil texture or grain size distribution alone. The new revision of NRCS's Tech Note 716, which is expected in 1998, will include more data for evaluating the hydraulic conductivity of soil based on soil texture. Hopefully, the revised Tech Note 716 will help us better quantify the uncertainty associated with using soil texture as a means of predicting seepage. In the meantime, a prudent engineering design should include other factors in addition to soil type, such as bulk density or compaction requirements, Atterberg limits, field and laboratory hydraulic conductivity and seepage measurements, and post-construction verification testing.

Although researchers have determined that animal waste causes a sealing effect thereby reducing seepage rates, research results have been mixed and there are differences of opinion as to whether the primary mechanism of sealing is chemical, biological, or physical. Until we know more about the sealing process, we should not rely on sealing as the primary mechanism for reducing seepage. Instead, the sealing should be looked upon as a conservative safety factor to assure that seepage rates will be lower than those accounted for with site-specific soils engineering design.

REGULATORY REVIEW

Regulatory information for California, Colorado, Iowa, Kansas, Missouri, Nebraska, and Texas was acquired from their respective environmental regulatory agencies in the summer of 1994 via phone interviews and a review of written state regulations (Parker et al., 1994; CCR, 1991; CWQCC, 1992; IAC, 1992; KDHE, 1978; KDHE, 1993; MCSR, 1990; MDNR, 1989; NDEQ, 1989). At that time, several state regulatory personnel mentioned that they were in the process of revising regulations. To compare the status and changes in state regulations in the past three years, the regulations for these eight states were reviewed again in late November, 1997, as were the additional six states of Idaho, Montana, New Mexico, North Carolina, Oklahoma, and South Dakota (CWQCC, 1997; IDEQ, 1993; ISDA, 1997; SNTC, 1993; IDNR, 1995; IEPC, 1997; KDHE, 1996; MDEQ, 1996; MDEQ, 1997; NDEQ, 1995; NMED, 1995a; NMED, 1995b; NCDEHNR, 1997; SOA, 1997; ODA, 1997; SDDENR, 1997a; SDDENR, 1997b; TNRCC, 1995a; TNRCC, 1995b; WAC, 1984; NRCS-Wisconsin, 1986). Information including maximum allowable infiltration rates, maximum allowable hydraulic conductivities, and earthen liner soil types and construction requirements were tabulated for each state (table 3). Between 1994 and 1997, two of the initial eight states (Nebraska and Texas) had finalized new regulations and another two (Iowa and Nebraska) were developing new regulations.

DISCUSSION OF REGULATORY REVIEW

This review has shown that states have taken widely different approaches in the way they regulate ponds and lagoons. Of the 14 states reviewed in 1997, six of the 14 states (Colorado, Idaho, Iowa, Kansas, Missouri, and Nebraska) regulated the maximum allowable seepage rate, with values ranging from 0.042 to 0.63 cm/day (table 3). Another six states (New Mexico, North Carolina, Oklahoma, South Dakota, Texas, and Wisconsin) regulated the maximum allowable hydraulic conductivity for earthen liners, with values ranging from 0.086 to 0.0086 cm/day. For the remaining two states, California's only requirement was for the type of soil used in earthen liners, while Montana's only requirement dealt with not exceeding a given nitrate concentration in the groundwater. In addition to liner requirements, several states also had requirements for sizing and locating of ponds and lagoons. Of the 14 states, only New Mexico did not specify the requirement for collection of runoff from the 25-year, 24-h storm event. In addition to the 25-year, 24-h requirement, Missouri also required containment from the 10-year, 10-day storm event.

Through our discussions with regulatory personnel, it became apparent that variations in state regulations were due to a combination of factors. One factor can be attributed to differences in politics among states, as some states are traditionally more environmentally conservative than others. However, it seems the biggest reason for differences among states is the variability in research results in which they based their regulations.

Regulations could be improved by making them proactive rather than reactive, and quantitative rather than subjective. For example, Montana's regulations state that, "a discharge of pollutants to state ground waters may only occur when seepage or leachate from a CAFO, combined with the volume of ground water beneath the source, results in a ground water nitrate-N concentration of less than 7.5 mg/L". This reactive approach is problematic in that regulations can only be enforced after contamination has occurred. In Texas, the regulations state that the operator of a CAFO must document that "no significant hydrologic connection exists between the contained wastewater and waters of the state". The phrase "significant hydrologic connection" is subjective and could have different meanings to different people. Nebraska's regulations state that retention facilities shall be located on soils which "will seal through sedimentation and biological action". Because both Texas and Nebraska have quantitative regulations governing the allowable seepage

Table 3. Comparison of state construction and infiltration regulations for animal waste lagoons and storage ponds

State	Max. Infiltration Rate (cm/day)	Max. Hydraulic Conductivity (cm/day)	Earthen Liner Construction Requirements
California	None specified	None specified	Liner must contain > 10% clay and < 10% gravel
Colorado	0.08	None specified	30.5 cm minimum compacted thickness
Idaho	0.86	None specified	Compacted to > 90% of standard proctor compaction
Iowa	0.16	None specified	Drill soil borings and test samples for hydraulic conductivity prior to operation, > 90% standard proctor compaction
Kansas	0.63 (applies to lagoons only)	None specified	15 cm minimum compacted thickness, > 95% standard proctor compaction, perform field or lab hydraulic conductivity tests after construction
Missouri	0.042 (potable GW) 0.29 (nonpotable GW)	None specified	30.5 cm minimum compacted thickness, > 90% modified proctor compaction, > 50% passing no. 200 sieve, liquid limit > 30, plasticity index > 20, classified as either CL, CH, GC, SC according to USCS classification
Montana	None specified	None specified	Discharge may only occur when seepage combined with groundwater results in nitrate concentration of less than 7.5 mg/L
Nebraska	0.63	None specified	Locate on soils which seal through sedimentation and biological action.
New Mexico	None specified	0.0086	30.5 cm minimum compacted thickness, > 95% standard proctor compaction, > 50% passing no. 200 sieve, plasticity index ≥ 10
North Carolina	None specified	0.0864 normally, or 0.0086 if bedrock < 1.2 m	30.5 cm minimum compacted thickness, or if bedrock is less than 1.2 m then a liner thickness selected depending on the "sensitivity of classified waters"
Oklahoma	None specified	0.0086	45.7 cm minimum compacted thickness, > 95% standard proctor compaction, maximum head of 3.2 m
South Dakota	None specified	0.0086	45.7 cm minimum compacted thickness, > 30% passing no. 200 sieve, liquid limit > 30, plasticity index > 15, classified as either CL or CH per USCS classification, compacted to "standard proctor density"
Texas	None specified	Subchapter B: None specified Subchapter K: 0.0086	Subchapter B Regs: > 30% passing no. 200 sieve, liquid limit ≥ 30%, plasticity index ≥ 15, 30.5 cm comp. thickness Subchapter K Regs: Requires documentation of no significant hydraulic connection with waters of the state
Wisconsin	None specified		No liner required if existing soil has > 50% passing no. 200 sieve, 2 options if < 50% passing
		0.0086 for Option 1	Option 1: 50% passing no. 200 sieve, 61 cm thickness on sides, 46 cm on bottom, > 90% standard proctor compaction, plasticity index 7 or greater, and hydraulic conductivity 0.0086 cm/day or less
		None for Option 2	Option 2: 50% passing no. 200 sieve, 76 cm thickness on sides, 61 cm on bottom, plasticity index 7 or greater, compact with minimum one pass with heavy equipment

rate or hydraulic conductivity, then these subjective statements only cause confusion and could be removed without affecting the intent or authority of the regulations. There is room for simplification and improvement of many of the other state's regulations also.

EDUCATIONAL NEEDS

After discussions with state regulators, reviewing written regulations and research manuscripts, and through day to day dealings with feedyard operators and environmental consultants and the public, it was apparent that there were still some misunderstandings concerning seepage from animal waste lagoons and storage ponds. Part of this misunderstanding can be attributed to the fact that animal waste management professionals have their own unique terminology (*ASAE Standards*, 1997). Confusion frequently occurs when terms are nonuniform, synonymous, or used in the wrong context, and this often leads to a misunderstanding and misinterpretation of environmental regulations and published research results.

The terms "lagoon" and "pond" are often used interchangeably, though they are quite different in purpose, design, and management. By definition, a lagoon is an impoundment designed for the "biological treatment" of animal wastewater (*ASAE Standards*, 1997). Lagoons are designed for a specific organic loading rate to control odors while reducing and stabilizing the waste. Storage ponds (or holding ponds) are impoundments designed for temporary storage of runoff and animal waste until such time as the contents may be recycled onto land (*ASAE Standards*, 1997). Storage ponds typically receive less concentrated wastewater and are shallower than lagoons. The terms "basin" and "hydraulic structure" are often used to mean pond, lagoon, or both.

Probably the biggest area of confusion regarding animal waste lagoon design and construction is the frequent failure to make the distinction between saturated hydraulic conductivity and seepage rate. In many situations, the terms "permeability" and "seepage rate" are used synonymously though they are quite different by definition. Hydraulic conductivity is a property of the soil and the fluids flowing within the soil. The term "hydraulic conductivity" is often used interchangeably with the term "permeability". For saturated flow, hydraulic conductivity and infiltration rate are related through Darcy's law, which states that the flow through soil is a product of the hydraulic conductivity of the soil and the hydraulic gradient:

$$q = K(h)\frac{\partial H}{\partial x} \tag{1}$$

where q is the infiltration or seepage rate (also called the Darcy velocity) with units of length/time, K(h) is the hydraulic conductivity at a pressure head, h, with units length/time, and $\partial H/\partial x$ is the hydraulic gradient. The hydraulic gradient is a measure of the mechanical driving force causing water to flow. The hydraulic gradient has units of length/length. The infiltration rate can change with time because of a changing hydraulic gradient.

Some of the confusion associated with environmental regulations could be solved by using consistent terminology. However, when we consider that people with different educational backgrounds are writing regulations in each state, problems with inconsistent terminology will likely not be solved anytime in the near future. As state regulatory agencies and/or USEPA revise and rewrite regulations, they would be well advised to follow ASAE standard terminology (*ASAE Standards*, 1997).

SUGGESTIONS FOR FUTURE RESEARCH

This review has identified several items that warrant further attention. There is little information concerning seepage rates from lagoons and ponds that have been in use for five years or longer. Methods need to be developed to determine if these lagoons and ponds need remediation and to rank the hazard of existing animal waste lagoons and storage ponds. These methods might include limited conventional sampling combined with non-intrusive techniques such as geophysical methods. Such information would be useful in developing a methodology to rank the hazard of existing animal waste lagoons and storage ponds.

Most of the field research has been limited to areas of shallow groundwater. Further research is warranted to evaluate effects on deeper groundwater, where the primary mode of transport to groundwater is unsaturated flow. Although it may take a longer time for contaminants to reach deep groundwater through unsaturated flow, the downside is that it will also take a long time to remediate the contamination.

Research has shown that wetting/drying cycles reduce the effects of sealing. The potential seepage loss from storage pond sideslopes subject to frequent water level fluctuations, wetting/drying and freezing/thawing is an area that warrants further research.

Little information has been gathered at low infiltration rates, due to limitations in laboratory measurement methods. Advances in technology now allow precise measurement of hydraulic conductivity (ASTM, 1996). Use of these new techniques would allow further characterization of infiltration rates for low permeability soils.

In previous field seepage measurements, water balances were used to determine seepage, assuming evaporation to be equal to that from a Class A pan using clear water. Because evaporation from an animal waste pond or lagoon is likely not the same as that from a Class A pan, research is warranted to compare evaporation from clear water and animal waste water.

Several studies have been performed to develop inexpensive methods of lining ponds. In this age of recycling and reuse, further research is warranted to evaluate innovative ideas for liners.

If physical, biological, or chemical sealing from animal waste is ever to be given credit in a regulatory sense for minimizing seepage when permitting a new animal waste lagoon or storage pond, then a method needs to be developed to account for sealing effects. The method should consider the many factors that affect sealing, including temperature, waste characteristics, depth to groundwater, soil structure and texture, pond depth, and frequency of pump down.

Development of a reliable, risk-based regulatory system that would appease regulators, operators, and the general public is a future research need. Not only would a risk-based system provide adequate environmental protection for high risk operations, but it would also benefit those small producers that operate a low risk operation or can't meet strict environmental regulations because of economic hardship. While the idea of a risk-based regulatory system sounds ideal and promising, the development of such a system would not be an easy task. This is primarily because we still cannot predict with high accuracy how much seepage to expect under different field conditions. For this reason, a new risk-based system should be probability-based, which would require human judgment to assign probabilities acceptable for environmental risk. The development of a reliable risk-based regulatory system is probably years in the future.

CONCLUSIONS

The results of this review demonstrate that much has been learned about seepage from ponds and lagoons, yet several questions remain unanswered. Researchers have determined that seepage and groundwater contamination can occur in earthen ponds and lagoons installed without any precautionary measures to minimize seepage (such as compacting the existing soil or installing a clay or geosynthetic liner). They have also determined that seepage rates are lower in fine-grained soils than in coarse-grained soils; however, our analysis shows that the universal application of this approach to all soil types may have some problems. Experiments designed to evaluate the magnitude and mechanisms of sealing due to animal waste have had variable results, indicating seal formation in some cases and not in others. It is still unknown how climatological factors might affect seal formation in field conditions. We also don't know how differences in evaporation rates between clear water and animal waste water might affect our water balance calculations for determining seepage rates in field conditions.

Most states have developed their own regulations governing seepage from animal waste ponds and lagoons. Of the 14 states reviewed, there was a broad variation in how seepage is regulated. Six states gave maximum allowable seepage rates, while another six gave maximum allowable hydraulic conductivities. This variability leads us to the biggest unanswered question at this time of "how much seepage is too much?". The time is right for a reliable, risk-based regulatory system that accounts for various site-specific factors such as depth to groundwater, location of the nearest surface water, soils characteristics, quality and use of the existing groundwater, local climatological conditions, and characteristics of the waste water in the pond or lagoon. Additional research is necessary to fully understand all of the facets of seepage from animal waste lagoons and storage ponds. As the knowledge base is increased, modification of environmental regulations will continue.

REFERENCES

ASAE Standards, 44th Ed. 1997. S292.5. Uniform terminology for rural waste management. St. Joseph, Mich.:ASAE.

ASTM. 1996. ASTM Method D 5084-90. Standard test method for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter. West Conshohocken, Pa.: American Society for Testing and Materials.

Barrington, S., and C. A. Madramootoo. 1989. Investigating seal formation from manure infiltration into soils. *Transactions of the ASAE* 32(3): 851-856.

Barrington, S. F., and P. J. Jutras. 1983. Soil sealing by manure in various soil types. ASAE Paper No. 83-4571. St. Joseph, Mich.:ASAE.

CCR. 1991. *California Code of Regulations, Regulations of the State Water Resources Control Board and the Regional Water Quality Control Boards*. Title 23, Div. 3, Ch. 15. Sacramento, Calif.

Chang, A. C., W. R. Olmstead, J. B. Johanson, and G. Yamashita. 1974. The sealing mechanism of wastewater ponds. *J. Water Pollution Control Fed.* 46(7): 1715-1721.

Ciravolo, T. G., D. C. Martens, D. L. Hallock, E. R. Collins Jr., E. T. Kornegay, and H. R. Thomas. 1979. Pollutant movement to shallow ground water tables from anaerobic swine waste lagoons. *J. Environ. Qual.* 8(1): 126-130.

Clark, R. N. 1975. Seepage beneath feedyard runoff catchments. In *Proc. 3rd Int. Symp. on Livestock Wastes*, 289-290. St. Joseph, Mich.:ASAE.

Culley, J. L. B., and P. A. Phillips. 1982. Sealing of soils by liquid cattle manure. *Canadian Agric. Engng.* 24(2): 87-89.

CWQCC. 1992. Confined animal feeding operations control regulation 4.8.0 (5CCR 1002-19). Denver, Colo.: Colorado Department of Publich Health and Environment, Water Quality Control Commission.

_____. 1997. Confined animal feeding operations control regulation No. 81 (5CCR 1002-81). Denver, Colo.: Colorado Department of Publich Health and Environment, Water Quality Control Commission.

Davis, S., W. Fairbank, and H. Weisheit. 1973. Dairy waste ponds effectively self-sealing. *Transactions of the ASAE* 16(1): 69-71.

Demmy, G. G., A. B. Bottcher, and R. A. Nordstedt. 1993. Measurement of leakage from dairy waste holding ponds. ASAE Paper No. 93-4017. St. Joseph, Mich.: ASAE.

DeTar, W. R. 1979. Infiltration of liquid dairy manure into soil. *Transactions of the ASAE* 22(3): 520-528, 531.

Hegg, R. O., T. G. King, and T. V. Wilson. 1979. The effects of groundwater from seepage of livestock manure lagoons. WRRI Tech. Report No. 78. Clemson, S.C.

Hills, D. J. 1976. Infiltration characteristics from anaerobic lagoons. *J. Water Poll. Cont. Fed.* 48(4): 695-709.

IAC. 1992. Environmental regulations and guidelines for animal feeding operations in Iowa. Iowa Administrative Code, Ch. 65 of the Environmental Protection Commission, Section 567. Des Moines, Iowa.

IDEQ. 1993. Idaho waste management guidelines for confined feeding operations. Twin Falls, Idaho: Idaho Division of Environmental Quality.

IDNR. 1995. Confinement feeding operation construction permit application form. Des Moines, Iowa: Iowa Department of Natural Resources.

IEPC. 1997. Proposed rules for confinement feeding operations. Des Moines, Iowa: Iowa Environmental Protection Commission.

ISDA. 1997. Livestock waste facility construction guidelines. Boise, Idaho: Idaho State Department of Agriculture.

KDHE. 1978. Minimum standards of design for water pollution control facilities. Topeka, Kans.: Kansas Department of Health and Environment.

_____. 1993. Design standards for confined livestock feeding operations. Topeka, Kans.: Kansas Department of Health and Environment.

_____. 1996. *Water Pollution Control Regulations*, Article 18. Topeka, Kans.: Kansas Department of Health and Environment.

MCSR. 1990. Design of small sewage works. In *Missouri Code of State Regulations*, 10 CSR 20-8.020. Jefferson City, Mo.

MDEQ. 1996. General discharge permit — Concentrated animal feeding operation. Helena, Mont.: Montana Pollutant Discharge Elimination System. Montana Department of Environmental Quality.

_____. 1997. Information packet for concentrated animal feeding operations, regulatory summary. Helena, Mont.: Montana Department of Environmental Quality.

MDNR. 1989. 2nd. Ed. Missouri Dept. of Natural Resources, Manual 121, *Design Guidelines for Animal Waste Management for Concentrated Animal Feeding Operations*. Jefferson City, Mo.

Miller, M. H., J. B. Robinson, and D. W. Gallagher. 1976. Accumulation of nutrients in soil beneath hog manure lagoons. *J. Environ. Qual.* 5(3): 279-282.

Miller, M. H., J. B. Robinson, and R. W. Gillham. 1985. Self-sealing of earthen liquid manure storage ponds: I. A case study. *J. Environ. Qual.* 14(4): 533-538.

Moffitt, D. C., J. Rickman, C. McElroy, D. Hendriks, H. Logan, and K. Kroeger. 1993. Do waste treatment lagoons leak? ASAE Paper No. 93-4526. St. Joseph, Mich.: ASAE.

NCDEHNR. 1997. North Carolina Administrative Code Section 15A NCAC 2H.0200: Waste not discharged to surface waters. Raleigh, N.C.: State of North Carolina Department of Environment, Health and Natural Resources.

NDEQ. 1989. Rules and regulations pertaining to livestock waste control, Title 130, Ch. 1-19. Lincoln, Nebr.: Nebraska Department of Environmental Quality.

_____. 1995. Rules and regulations pertaining to livestock waste control, Title 130, Ch. 1-19. Lincoln, Nebr.: Nebraska Department of Environmental Quality.

NMED. 1995a. Guidelines for liner material and site preparation for synthetically-lined lagoons. Santa Fe, N.Mex.: New Mexico Environment Department Ground Water Pollution Prevention Section.

_____. 1995b. Guidelines for liner material and construction of clay-lined lagoons. Santa Fe, N.Mex.: New Mexico Environment Department Ground Water Pollution Prevention Section.

Norstedt, R. A., L. B. Baldwin, and C. C. Hortenstine. 1971. Multistage lagoon systems for treatment of dairy farm waste. In *Proc. Int. Symp. on Livestock Wastes*, 77-80. St. Joseph, Mich.: ASAE.

NRCS-Wisconsin. 1986. NRCS manure storage Standard 313 and 425, Section IV, *Technical Guide*. Madison, Wis.: Natural Resource Conservation Service.

ODA. 1997. Rules for concentrated animal feeding operations. Title 35, Ch. 17, Subchap. 3. Oklahoma City, Okla.: Oklahoma Department of Agriculture.

Parker, D. B., D. D. Schulte, D. E. Eisenhauer, and J. A. Nienaber. 1994. Seepage from animal waste lagoons and storage ponds — Regulatory and research review. In *Proc. Great Plains Animal Waste Conference on Confined Animal Production and Water Quality*, eds. D. E. Storm, and K. G. Casey, 87-98. Denver, Colo.: Great Plains Agricultural Council.

Parker, D. B., D. E. Eisenhauer, D. D. Schulte, and J. A. Nienaber. 1999. Seepage characteristics and hydraulic properties of a feedlot runoff storage pond. *Transactions of the ASAE* 42(2): 369-380.

Phillips, P. A., J. L. B. Culley, J. M. Leclerc, and C. Fox. 1983. Groundwater seepage from earthen manure storages in eastern Ontario. ASAE Paper No. 83-4570. St. Joseph, Mich.: ASAE.

Reese, L. E., and T. L. Loudon. 1983. Seepage from earthen manure storages and lagoons, A literature review. ASAE Paper No. 83-4569. St. Joseph, Mich.: ASAE.

Ritter, W. F., E. W. Walpole, and R. P. Eastburn. 1984. Effect of an anaerobic swine lagoon on groundwater quality in Sussex County, Delaware. *Agricultural Wastes* 10(4): 267-284.

Robinson, F. E. 1973. Changes in seepage rate from an unlined cattle waste digestion pond. *Transactions of the ASAE* 16(1): 95-96.

Rowsell, J. G., M. H. Miller, and P. H. Groenevelt. 1985. Self-sealing of earthen manure storage ponds: II. Rate and mechanism of sealing. *J. Environ. Qual.* 14(4): 539-543.

Sewell, J. I. 1978. Dairy lagoon effects on groundwater quality. *Transactions of the ASAE* 21(5): 948-952.

Smith, S. J., B. A. Stewart, A. N. Sharpley, J. W. Naney, T. McDonald, M. G. Hickey, and J. M. Sweeten. 1993. Nitrate and other nutrients associated with playa storage of feedlot wastes. B-5081. College Station, Tex.: Texas A&M University.

SDDENR. 1997a. General water pollution control permit for concentrated swine feeding operations. Pierre, S.Dak.: South Dakota Department of Environment and Natural Resources.

_____. 1997b. Draft general water pollution control permit for concentrated animal feeding operations. Pierre, S.Dak.: South Dakota Department of Environment and Natural Resources.

SNTC. 1993. Design and construction guidelines for considering seepage from agricultural waste storage ponds and treatment lagoons. Technical Note No. 716, Rev. 1. Fort Worth, Tex.: U.S. Dept. of Agric. Natural Resource Conservation Service (formerly Soil Conservation Service). South Nat. Tech. Center.

SOA. 1997. State of Oklahoma concentrated animal feeding operations act. House Bill No. 1522. Oklahoma City, Okla.

Sweeten, J. M. 1992. Groundwater quality protection for livestock feeding operations. Bulletin B-1700. College Station, Tex.: Texas Agricultural Experiment Station, Texas A&M University.

TNRCC. 1995a. Animal waste management rules — Subchap. B: Livestock and poultry production operations. Ch. 321. Austin, Tex.: Texas Natural Resource Conservation Commission.

_____. 1995b. Animal waste management rules — Subchap. K: Concentrated animal feeding operations, 321.181-321.198. Austin, Tex.: Texas Natural Resource Conservation Commission.

WAC. 1984. Animal waste management. Wisconsin Administrative Code, Ch. NR 243.01-243.26. Madison, Wis.

Westerman, P. W., R. L. Huffman, and J. S. Feng. 1995. Swine-lagoon seepage in sandy soil. *Transactions of the ASAE* 38(6): 1749-1760.