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Keywords

Lagoon, Pit, Seepage, Regulation

Disciplines

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Comments

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MEASUREMENT OF LEAKAGE FROM EARTHEN MANURE STRUCTURES IN IOWA

T. D. Glanville, J. L. Baker, S. W. Melvin, M. M. Agua

ABSTRACT. *Leakage from a representative sample of 28 earthen manure storage structures and lagoons (selected from 459 built in Iowa between 1 January 1987 and 31 December 1994) was determined using a water–balance approach. Forty–three percent (43%) of tested structures had leakage rates significantly ($p < 0.05$) lower than the regulatory limit of 1.6 mm/d (1/16 in/d) specified by the State of Iowa at the time the basins were constructed. Leakage from 53% of the structures was too close to the regulatory limit to be categorized as being significantly above or below it. One structure (4%) exhibited leakage significantly greater than the regulatory limit. Regression analysis indicates a slight, but statistically significant, decline in leakage rate with increasing structure age. Structures constructed in glacial till showed significantly lower leakage rates than those constructed in sand and gravel, colluvium, or loess. Comparison of slurry pits and lagoons showed no significant difference in leakage rate.*

Keywords. *Lagoon, Pit, Seepage, Regulation.*

Leakage from earthen structures designed to store and/or treat animal manure has been the focus of numerous studies and regulatory programs in the U.S. during the past four decades. In their summary of literature on this subject, Louden and Reece (1983) reviewed the results of more than 20 leakage–related studies published between 1965 and 1982. Subsequent literature reviews by Parker et al. (1994, 1999) identified numerous field– and laboratory–scale studies conducted during the 1980s and 1990s and reported widely differing approaches in the way 14 states regulate leakage from earthen manure structures (EMS). In a review of livestock waste regulations in 13 southeastern states, Hegg (1997) reported that at least four states in that region were in the process of modifying their regulations. Jones and Sutton (1996) noted that 1996 regulations in 12 midwestern states were more stringent with regard to manure storage structure design and approval than they were in 1992 when a similar survey was conducted.

More recently, Copeland and Zinn (1998) reported that at least 20 state legislatures considered bills to further regulate livestock production during their 1998 legislative sessions. In 1998, the U.S. Environmental Protection Agency released the first draft of its *Strategy for Addressing Environmental and Public Health Impacts from Animal Feeding Operations* (USEPA, 1998), a document touted as a “blueprint for a significant expansion of USEPA’s regulatory and voluntary efforts related to animal feeding operations.” A parallel program by the Natural Resources Conservation Service of the U.S. Department of Agriculture provides technical guidance on design and construction of manure storage ponds and treatment lagoons through its new geotechnical, design, and construction guidelines (NRCS, 1997).

Responding to policymakers’ demands for more definitive information on leakage from earthen manure structures, new studies have been initiated in several states. Nearly half of eleven 10–20 yr old lagoons studied in North Carolina exhibited significant leakage characterized by elevated ammonium–nitrogen (NH_4–N) concentrations in down–gradient soil samples (Huffman and Westerman, 1995; McMahon, 1995). Groundwater monitoring near two new swine lagoons constructed in deep sandy soils in North Carolina indicated significant leakage via preferential flow paths after 3–5 yr of service (Westerman et al., 1995). During a field evaluation of risk–based lagoon–siting criteria, no evidence of leakage was found near five lagoons located in “low vulnerability” settings. Groundwater near three of four lagoons at “moderately vulnerable” sites exhibited increased concentrations of nitrate–nitrogen (NO_3–N) and chloride (Cl), and elevated concentrations of NH_4–N, NO_3–N, and potassium (K) were found near one of two lagoons in “vulnerable” settings (North Carolina Division of Water Quality, 1998). Four years of groundwater monitoring near three EMS in Iowa revealed increased Cl, NH_4–N, and total organic carbon concentrations beneath the berms of two earthen structures. At locations further down gradient, Cl increased significantly at one of the three sites (Libra and Quade, 1997).

Although many states specify maximum allowable daily leakage from EMS, relatively few studies have attempted to measure whole–basin leakage in operational earthen structures. A dairy manure storage pond in Minnesota was

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constructed with a special underdrain system that permitted capture and direct measurement of leakage through portions of the bottom and sidewalls. Results showed significantly greater leakage through the sidewalls than the floor during the first year of operation. Sealing of the floor by solids deposition, and differences between sidewall and floor compaction during construction, were believed to be the most likely causes for these results (Hetchler and Clanton, 1996; Swanberg, 1997). Water balance studies of whole–lagoon leakage from 12 swine–, 2 cattle–, and 2 dairy–waste lagoons in Kansas indicate leakage losses ranging from 0.2 to 2.4 mm/d (Ham and DeSutter, 1998, 1999, 2000). Ham (2000) provides a thorough review of equipment and methods for conducting water balance studies of whole–lagoon leakage.

PROJECT BACKGROUND AND OBJECTIVES

In May of 1997, the Iowa legislature directed Iowa State University to conduct a statewide study of the effects of earthen manure structures on water quality, and to report its findings to the legislature by January of 1999. With more than 600 EMS located in a variety of hydrogeologic settings, and fewer than 12 months of suitable weather in which to conduct the study, the research team concluded that there would be insufficient time to conduct typical groundwater monitoring studies. To meet the tight legislative timeline, a four–part study was designed to assess four indicators of potential water quality impact that could be rapidly evaluated at each site. The four phases of the project involved were: (1) measurement of daily whole–basin leakage; (2) measurement of NH_4–N, NO_3–N, Cl, and sulfate (SO_4) in shallow soil cores collected from around EMS; (3) statistical assessment of surface water and groundwater pollution potential based on aerial photos, topographic maps, and soils data; and (4) development of case histories of operating practices through interviews with EMS managers. Results of the whole–basin leakage measurement study are reported here. Outcomes of the other three phases of the project are presented elsewhere (Baker et al., 1999; Simkins et al., 1999; Richard et al., 1999).

The rationale for attempting to measure whole–basin leakage included the following potential benefits:

- It was believed that whole–basin leakage measurements could be made at each site in 10 d or less, making it feasible to collect data from 30–40 sites within the allotted project time frame.
- Iowa environmental regulations specify maximum leakage rates, which provide a benchmark of legally acceptable performance: structures that received a construction permit from the Iowa Department of Natural Resources prior to 21 January 1998 are limited to maximum leakage of 1.6 mm/d when measured at a liquid depth of 1.8 m (6 ft), regardless of actual design depth; structures that received permits after 21 January 1998 must meet a more stringent leakage limit of 1.6 mm/d when filled to design depth.
- Unlike groundwater monitoring, the success of whole–basin leakage measurements does not rely on identifying the location of the leakage.
- When combined with chemical concentration data for liquid manure contained within the EMS, whole–basin leakage measurements make it possible to quantify pollutant transport into the soil.
- Successful development of whole–basin leakage measurement techniques would provide a potentially useful tool for regulatory agencies, engineers, and owners of EMS.

Objectives for the leakage measurement study included: (1) identification and evaluation of commercially–available transducers that can accurately measure short–term liquid–level fluctuations caused by leakage; (2) development of protocols for collecting and analyzing liquid–level and meteorological data of sufficient quantity and quality to permit leakage determination via water–balance calculations; (3) measurement of leakage in approximately 10% of the 439 EMS constructed in Iowa between 1987 and 1994, and estimation of the percentage of structures meeting State of Iowa leakage limits; and (4) analysis of leakage rates for trends relating to structure type (lagoon or slurry basin), structure age, and subsoil characteristics.

METHODS

SITE SELECTION

As an EMS ages, a variety of natural processes affect the compacted soil liner and its ability to retain liquid. Processes that tend to increase leakage include liner cracking caused by repeated freeze/thaw and wetting/drying cycles; intrusion by earthworms, rodents, or roots; erosive effects of wave action or improper mechanical agitation; and localized erosion of the compacted soil liner caused by groundwater infiltration after an EMS is emptied. Counteracting these processes are the sealing effects of accumulated organic matter, which may decrease the leakage rate with time. To help ensure that leakage measurements made during the study would reflect the normal effects of aging, the research team decided that all study sites should be at least three years old (i.e., constructed prior to the end of 1994).

A query of the Iowa Department of Natural Resources (IDNR) electronic database of livestock facilities identified a target population of 439 slurry basins and lagoons constructed between 1 January 87 and 31 December 94 (a small number of older structures are not included in the IDNR electronic database). Owners or managers of all facilities in the target population were contacted and invited to participate in the study. One hundred twenty four volunteered to participate and completed a questionnaire concerning their operations and facilities. A sample comprised of 40 facilities (9.2% of target population) was selected such that the ratio of slurry basins to lagoons mirrored that of the target population (70% slurry basins, 30% lagoons). Anticipating that local hydrogeology would affect leakage rates, the sample was also selected so that the proportion of facilities located within each of five major groundwater vulnerability regions (Hoyer and Hallberg, 1991) was similar to the target population.

INSTRUMENTATION AND DATA COLLECTION

Discussions with several instrument manufacturers and vendors (Campbell Scientific, Druck Incorporated, Kobold Instruments) revealed that liquid–level sensors costing less than $1000 are typically pressure diaphragm units designed to monitor water level fluctuations over a range of at least

0.6 m (2 ft). With typical full–scale accuracies of 0.1%, these devices are capable of resolving water level fluctuations of about 0.6 mm (0.024 in) or the equivalent of about 9 h of leakage at Iowa’s maximum allowable leakage rage of 1.6 mm/d. Since wind “noise” can seriously interfere with identification of the small steady decline in liquid levels caused by leakage, it was anticipated that leakage measurements would likely need to be based on data sequences collected during infrequent periods of calm lasting as little as one hour. To accomplish this, the liquid–level sensing system needed to be capable of detecting liquid–level changes at least as small as the hourly equivalent (0.067 mm/h) of Iowa’s regulatory leakage limit, a resolution 10 times better than that offered by commercially available sensors.

Since an affordable commercially fabricated liquid–level sensor having the desired resolution was not readily available, the research team proceeded with design and testing of instrumentation that could meet project requirements. The liquid–level monitoring system illustrated in figure 1 was conceived and field–tested during spring of 1998. It employs a siphon tube providing hydraulic connection between liquid within the earthen structure and water in a beaker that is positioned on a portable electronic balance located on the opposite side of the berm. Liquid–level fluctuations in the EMS cause fluctuations of the same amplitude within the beaker. Resulting changes in the liquid mass within the beaker are sensed by the balance and recorded by a data logger. For the 10.1–cm diameter beakers used in this study, a liquid–level fluctuation of 1 mm caused an 8–g change in liquid mass. Since the electronic balance was capable of resolving changes in mass of 0.1 g, this system is theoretically capable of resolving liquid–level fluctuations of 1/80 mm (0.012 mm, or 0.0005 in). As such, this system is nearly 50 times more sensitive than the previously described pressure diaphragm sensors, and is capable of detecting the liquid–level changes that would occur in 0.2 h in structures leaking at Iowa’s regulatory leakage limit.

In addition to measuring water level fluctuations inside the earthen structure, a second siphon tube and balance system was used to measure evaporation of clear water placed in a 0.56 m (22 in) diameter pan positioned on the outer slope of the berm. Each monitoring site was also instrumented to record precipitation, wind speed and direction, air temperature, and relative humidity. All water level and meteorological data were logged at 2–min intervals using a Campbell Scientific CR10X data logger.

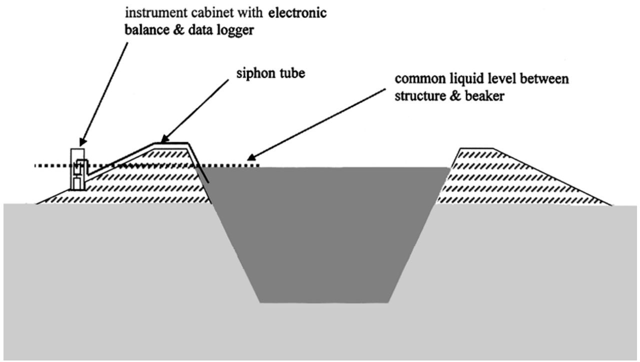

Figure 1. Schematic of liquid–level measurement system using a siphon tube, battery–powered electronic balance, and data logger.

LEAKAGE DETERMINATION

Water Balance Relationship

Leakage from EMS included in this study was calculated using the general water balance relationship:

$$\text{Inputs} - \text{Outputs} = \text{Change in storage} \qquad (1)$$

For the purposes of this study, evaporation and change in liquid level (reflecting change in storage) were the only variables that needed to be measured. The need to quantify other potential inputs and outputs such as precipitation and piped discharges into and out of the EMS was avoided by confining leakage determinations to time periods when no rainfall was detected, and by requiring cooperating facility owners to discontinue all piped flows during leakage monitoring.

With the values for precipitation and piped flows constrained to zero, the water balance equation can be expressed as:

$$-[\Delta L_E \text{ (mm/d)} + \Delta L_L \text{ (mm/d)}] = \Delta L_S \text{ (mm/d)} \qquad (2)$$

where

ΔL_E = rate of change in liquid level caused by evaporation

ΔL_L = rate of change in liquid level due to leakage (calculated)

ΔL_S = rate of change in liquid level measured within the EMS in the field.

Values for ΔL_E and ΔL_S were obtained from selected data sequences by plotting liquid levels (mm) versus time (d) and determining the slope (mm/d) of the linear regression line through each data sequence, as illustrated in figure 2.

Conversion of Field Leakage Rates to Equivalent Leakage Rates at Regulatory Depth

Since leakage from earthen structures is proportional to hydraulic gradient, leakage measurements at different sites cannot be compared unless they have been adjusted to a common depth. More specifically, comparisons with regulatory leakage limits require that field measurements be adjusted to the depth conditions specified by the regulations (1.8 m for Iowa EMS constructed prior to 21 January 1998).

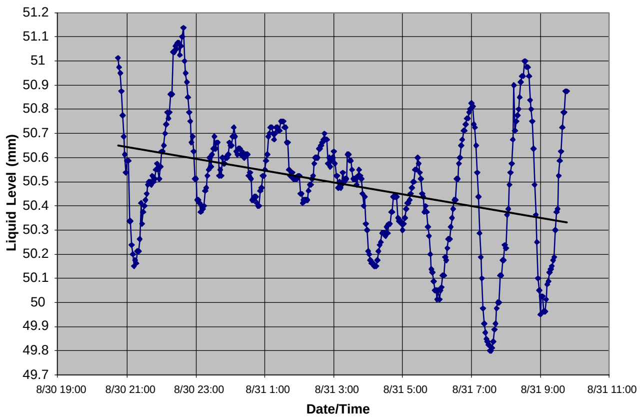

Figure 2. Example of liquid–level data recorded within an earthen structure affected by moderate (<1.5 m/s) wind; slope of regression line indicates gradual decline due to leakage and evaporation.

Using Darcy's law, field leakage measurements (V_F) can be related to the thickness of the compacted soil liner (T), saturated hydraulic conductivity of the liner (K), and the total head (H_F) at the time field measurements were made (eq. 3). Similarly, the equivalent regulatory leakage velocity (V_R) is a function of K, T, and total head (H_R) at the liquid depth (1.8 m) specified by state leakage regulations (eq. 4):

$$V_F = K\ (H_F/T) \tag{3}$$

$$V_R = K\ (H_R/T) \tag{4}$$

Combining equations 3 and 4, and recognizing that K and T are constants for any particular research site, $V_R/V_F = H_R/H_F$, and V_R can be calculated using:

$$V_R = V_F\ [H_R/H_F] \tag{5}$$

Total head loss across the compacted liner (H_R or H_F) is computed as:

$$H = D + T - D_{GW} \tag{6}$$

where

D = liquid depth above the compacted earthen liner

D_{GW} = height of the local water table above the bottom of the compacted liner

T = thickness of the liner.

Because as–built plans were not available for the structures that were monitored, conversions from V_F to V_R were based on the assumption T = 30.5 cm (1 ft). This assumption was made because, since the mid–1980s, earthen structures in Iowa have been required to undergo percolation tests following construction to verify that leakage is no greater than 1.6 mm/d (when D = 1.8 m as specified by state regulations). In most cases, this leakage limit has been met through construction of compacted earthen liners ranging from 15 to 30 cm in thickness. In cases where the true value of T is less than 30 cm, the values of H_R and H_F would be reduced by as much as 15 cm. Since field measurements for this project were made at a time of year when liquid manure depths (D) inside the earthen structures were nearing design depth, H_F was typically two to three times greater than H_R. As a result, a 15–cm reduction for H_R is proportionately greater than for H_F. This results in a slight reduction in the value of H_R/H_F, making the true value of V_R (using eq. 5) slightly smaller than that obtained using the assumed value of 30 cm for T. The overestimation of V_R caused by the assumption is not large. Using H_R = 1.8 m, H_F = 4.6 m (mean design depth for earthen structures monitored), and D_{GW} = 0 cm, the calculated value for V_R is 0.42 V_F when T = 15 cm, while V_R = 0.43 V_F when T is assumed to be 30 cm.

Determination of D_{GW} was complicated by a lack of water table elevation data, and by project time constraints that ruled out installation of new piezometers solely for the purpose of monitoring the water table. In some instances, approximate water table elevations were obtained by installing temporary casings inside 2.5–cm diameter holes created by extraction of 2.4 m (8 ft) deep soil cores from around the outer toe of the berm. At slightly more than one–third of the study sites, however, the water table was not intersected by the shallow core holes. The previously noted lack of as–built plans further complicated estimation of D_{GW} since the exact elevation of the bottom of the compacted soil liner was unknown.

In light of the uncertainties regarding D_{GW}, values of V_R presented in this article are based on the assumption that D_{GW} = 0. In situations where the water table is below the bottom of the compacted liner ($D_{GW} < 0$), the true value of D_{GW} becomes the soil matric potential. In soils moistened by leakage, soil matric potential is a relatively small value compared to D or T, making the assumption that D_{GW} = 0 a reasonably accurate estimate.

In a few instances, the true value of D_{GW} may have exceeded zero at the time leakage data were collected. Although leakage monitoring was conducted during late summer and fall, when water tables typically approach their lowest levels, published soils data suggest that the water table may have been above the bottom of the compacted soil liner ($D_{GW} > 0$) at some sites. Analysis of the published data by Simpkins et al. (1999) indicates that nearly 65% of the EMS studied are located at sites where depth to water table is less than 1.5 m (5 ft) during wet seasons.

As with the previously described errors caused by overestimation of T, underestimation of D_{GW} similarly inflates the estimated values of H_R and H_F by the same absolute amount, resulting in overestimation of H_R/H_F and V_R in equation 5. If, for example, the true value of D_{GW} = 1 m, then H_R/H_F = 0.28 (for H_R = 1.8 m, T = 0.3 m, and H_F = mean design depth of 4.6 m), while H_R/H_F = 0.43 under the assumption that D_{GW} = 0.

Data Selection

Uncontrollable liquid–level fluctuations caused by precipitation, wind, and variations in evaporation rate can obscure the slow liquid–level decline caused solely by leakage. As noted earlier, these effects are temporal and can be minimized by restricting leakage determinations to data sequences collected during periods of minimal disturbance. To help ensure a consistent approach to selection of data sequences for analyses, a data–scanning program was written to identify sequences collected during periods meeting specific rainfall, wind speed, and relative humidity criteria. As previously noted, a zero precipitation criterion was applied to minimize measurement errors associated with spatially varied rainfall.

To reduce wind–related effects, a peak wind–speed criterion of 3 m/s was used. Figure 2 illustrates the relatively minor (amplitude approximately 1 mm) liquid–level fluctuations caused by wind speeds averaging less than 1.5 m/s at one site. Steady winds of sufficient velocity and duration can cause "wind tides", characterized by temporal rises in liquid levels near the downwind shoreline (or declines near the upwind shore). The peak wind speed criterion was selected through trial and error, and generally produced data sequences with average wind speeds of 2m/s or less. Trials using a lower wind speed criterion seriously limited the number of useable data sequences.

Accurate measurement of evaporation from EMS is the most difficult aspect of leakage determinations made using a water balance approach. Differences in solar energy gain and wind exposure often cause pan evaporation measurements to exceed the true evaporation from larger bodies of water. Pan coefficients ranging from 0.7 to 0.9 (Brutsaert, 1982; Burman and Pochop, 1994) are typically used to crudely correct pan data for evaporation from freshwater lakes or reservoirs. Selection of an appropriate pan coefficient is difficult at best for freshwater bodies, and is even more difficult for liquids, like manure, that may be partially covered by floating material or contain non–homogeneous suspended and dissolved solids that affect solar energy absorbance. Recent studies by Ham and DeSutter (1999) have focused on improving the accuracy of lagoon evaporation measurements by floating the evaporation pan in the lagoon liquid. Their results have shown, however, that daytime surface temperatures inside floating pans often exceeded those in lagoons, and that pan coefficients ranging from 0.69 to 0.94 were needed to correct the floating pan data (Ham, 2000). A variety of meteorological equations have been developed to predict pan coefficients or to directly calculate evaporation (Dingman, 1994). Use of these relationships, however, requires collection of substantial amounts of meteorological data, and as with the pan measurements themselves, ensuring that these data are representative of conditions at the surface of the lagoon can be quite difficult.

In light of the numerous complexities associated with accurate evaporation measurement, it should be noted that ultimately all leakage values presented in the Results section of this paper were calculated assuming zero evaporation occurred during leakage monitoring. Consistent with previously described assumptions regarding the values of T and D_{GW}, the zero evaporation assumption yields higher calculated values of leakage since the measured decline in the liquid level within an EMS is attributed solely to leakage. As such, the leakage rates presented in subsequent sections are believed to represent the upper limit of leakage. While this approach provides only an approximation of the true leakage rate, project investigators felt that the legal, regulatory, and social issues that originally caused the Iowa legislature to mandate this study were better served by quantifying the upper limit of leakage than by providing less–conservative leakage estimates that might be challenged as being unfairly biased in favor of Iowa's largest industry.

Errors associated with assuming zero evaporation have been minimized to the extent possible by limiting leakage calculations to data sequences collected when evaporation rates were as near to zero as possible. To help accomplish this, a minimum relative humidity criterion of 90% was added to the data–scanning algorithm. When applied in conjunction with the previously described maximum wind speed criterion, nearly all leakage calculations were made using data collected at night when solar energy gain is zero, air and water surface temperatures are typically at a 24–h low, and relative humidity is at a 24–h high.

RESULTS

USEABLE DATA SEQUENCES

Although 40 EMS were originally selected for study, liquid–level measurements could not be obtained at all locations. Five research sites were dropped because their owners failed to return the memorandum of understanding granting project personnel permission to enter their property. Liquid levels at four sites were sufficiently far below surrounding ground elevation that they could not be monitored using the siphon and balance instrumentation system, and one site had been abandoned by its owners. Data collected at a university–owned lagoon during design and testing of instrumentation was ultimately added to the study, bringing the total number of monitored sites to 31 (7.1% of the target population of 439 EMS).

Using the data selection criteria for precipitation, wind speed, and relative humidity, 76 liquid–level data sequences were obtained at 28 of the 31 EMS tested. Due primarily to wind interference, concurrent pan evaporation measurements were obtained for only 60% of the 76 data sequences. The duration of usable data sequences collected during the 5– to 10–day monitoring period at each EMS ranged from 164 to 2614 min, with a mean of 1132 min and a standard deviation of 673. Inclement weather or equipment malfunctions prevented collection of data meeting the selection criteria at three of the 31 research sites. Project time constraints precluded spending more time at these three sites.

EVAPORATION RATE

The increase in estimated leakage caused by the assumption of zero evaporation was estimated using two strategies. Pan evaporation data from the 43 useable evaporation data sequences yielded evaporation rates ranging from <0.01 to 1.79 mm/d, with a mean value of 0.56 mm/d. Applying the previously discussed pan coefficients of 0.7 to 0.9 to the mean evaporation rate suggests evaporation from the earthen structures was in the range of 0.39 to 0.50 mm/d.

To check the validity of the average evaporation estimate derived from the pan data, a simplified evaporation prediction equation (eq. 7) based on mass–transfer theory was applied. This prediction equation (Dingman, 1994) is:

$$E = K_E \, \nu_a \, (\rho_s - \rho_a) \qquad (7)$$

where

E = predicted evaporation rate (cm/d)
K_E = mass transfer coefficient of approximately 1.26×10^{-4} (sec/mb–day)
ν_a = measured wind speed (cm/sec)
ρ_s and ρ_a = vapor pressures (mb) at the liquid surface and in the air (calculated from temperature and relative humidity).

At temperatures of 10° to 20°C (assuming water surface and air temperatures are roughly the same), average wind speeds of 1.5 to 2.0 m/s, and a relative humidity of 95%, equation 7 predicts evaporation rates in the range of 0.15 to 0.35 mm/d.

LEAKAGE RATE

Figure 3 shows adjusted (to regulatory depth of 1.8 m) mean daily rates of liquid–level decline (caused by both leakage and evaporation) at each of the 28 EMS sites for which data sequences were available. These values were obtained by averaging the slopes of linear regression lines drawn through the selected sequences of liquid–level versus time data for each EMS, as illustrated in figure 2. The 95% confidence bands in figure 3 indicate that the mean rate of liquid–level decline at some sites lies somewhere within a range spanning 1 mm/d or more. Differences in the widths of the 95% confidence intervals are caused by two factors. Favorable wind, precipitation, and relative humidity conditions at some sites permitted collection of a larger number of useable data sequences. Since mean values for these sites are the result of a larger number of leakage observations, their confidence intervals are narrower. Statistical analysis also revealed that data variability at each EMS tended to be proportional to the mean, resulting in broader confidence intervals for sites exhibiting higher rates of liquid loss.

Although true leakage may be as much as 0.2 to 0.4 mm/d less (due to evaporation) than the calculated mean loss rates shown in figure 3, the width of the confidence bands also suggest that making such small evaporation corrections implies more precision in the leakage determinations than can realistically be claimed. In light of this, and as previously explained, the "leakage" rates presented here have not been corrected for evaporation and are believed to represent the upper limit for the true leakage.

To determine the proportion of sites with leakage significantly above the regulatory limit, a one–sided t–test was conducted. Results indicate that 12 of 28 sites (43%) had leakage rates significantly ($p < 0.05$) less than the regulatory limit, and only one site (4%) had leakage significantly above the original regulatory limit. Leakage rates at the remaining 15 sites (53%) were sufficiently close to the 1.6 mm/d limit that they could not be declared significantly larger nor significantly smaller than the limit. Recognizing again that the leakage estimates shown in figure 3 are overestimates of the true leakage due to previously stated assumptions regarding evaporation, depth to water table, and thickness of the compacted soil liner, the proportion of sites meeting Iowa's leakage limit is believed to be greater than 43%.

EFFECTS OF SOIL TYPE, AGE, AND MANURE SOLIDS CONCENTRATION

To evaluate siting and design factors that may affect long–term leakage from earthen structures, mean leakage values were statistically tested for evidence of trends or differences associated with age, soil characteristics, and type of storage (undiluted manure slurry storage basin versus diluted manure treatment lagoon). Analyses were based on data from 27 of the 28 sites that were monitored. Data for the EMS having the greatest leakage rate (site #17) had nearly three times the leakage of any other site) were omitted from these analyses since the abnormally high leakage rate may have been caused by serious construction deficiencies or other leakage mechanisms that are not characteristic of EMS in general. Moreover, inclusion of the highly variable leakage data for this structure hampers the ability to statistically identify possible differences due to age, soils, or type of storage.

Relationship of Leakage to Soil Type

Based on soils data, topographic maps, and aerial photography, project geologists categorized each EMS according to the dominant types of geologic materials (Simpkins et al., 1999) underlying the site. Study sites were grouped into four general categories: sand and gravel, colluvium, loess, and till.

As shown in figure 4, mean leakage rates were highest (1.67 mm/d) for EMS constructed in or above sand and gravel (alluvial) materials. Mean leakage was lowest (0.92 mm/d) at sites where glacial till was the predominant underlying material. Since the hydraulic conductivity of fine sands often exceeds that of glacial till by two or more orders of magnitude, the relatively small difference between the average leakage rates for till and sand/gravel sites suggests that leakage is influenced mainly by the hydraulic conductivity of the compacted soil liner and accumulated sludge on top of the liner, rather than by the underlying soil material.

Statistical analysis verified that mean leakage rates for EMS constructed in till were significantly ($p < 0.05$) lower than for structures constructed in non–till (sand and gravel, colluvium, or loess) materials. There were no statistically significant differences, however, among leakage rates for EMS constructed in loess, colluvium, or sand and gravel.

Relationship of Leakage to Structure Age

One of the long–standing questions concerning earthen structures is whether leakage rates increase or decrease over time. Early thoughts on the subject tended to support the idea that earthen structures "self–seal" over time. More recent work suggests that processes such as freezing and thawing, wetting and drying, wave erosion, and intrusion by earthworms, roots, or rodents may lead to increased leakage as earthen structures age.

Since structures constructed in "till" and "non–till" (sand and gravel, colluvium, loess) soil types were found to have significantly different leakage rates, it was necessary to aggregate the data into "till" and "non–till" groupings before regressing leakage rates against structure age. As indicated

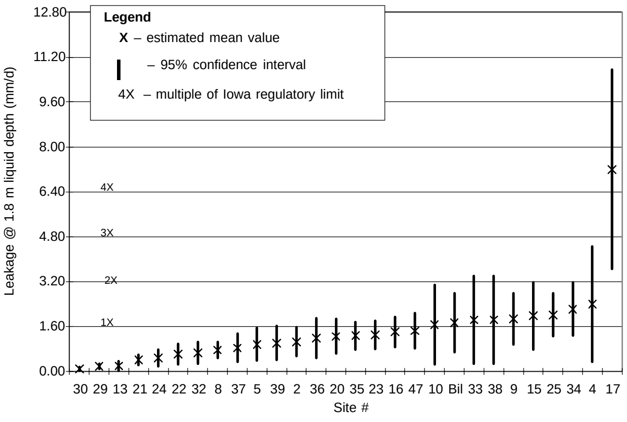

Figure 3. Estimated mean leakage rates (calculated assuming zero evaporation) and 95% confidence intervals for 28 earthen manure structures at a liquid depth of 1.8 m (6 ft).

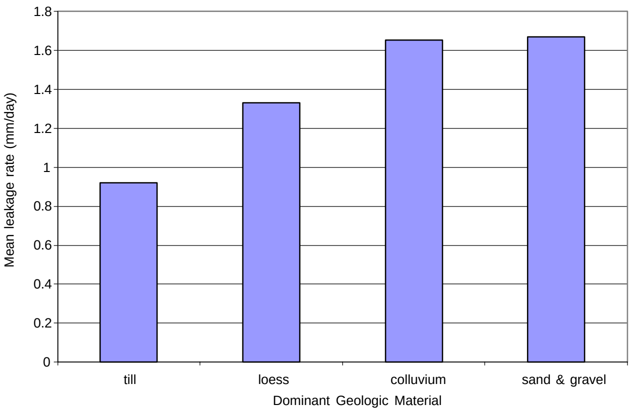

Figure 4. Mean leakage rates (at 1.8 m liquid depth) for earthen manure structures grouped by dominant surficial geologic material.

by the scatter in the data (fig. 5), the trend with age is not particularly strong. However, the slopes of the linear regressions through the till and non–till data are nearly identical (–0.16 mm d^{-1} yr^{-1}), and a t–test indicates that this slope is significantly different ($p < 0.05$) from zero. Since the project was designed to study structures that were at least three years old, no conclusions can be drawn regarding leakage rates immediately following construction.

Comparison of Slurry Pits and Lagoons

Since slurry pits typically have smaller surface areas and contain manure with higher solids content than lagoons, solids deposition and sealing potential in slurry pits might reasonably be expected to be higher than for lagoons. For the 12 lagoons and 15 slurry pits tested (excluding the single site with extreme leakage), mean leakage at the regulatory liquid depth of 1.8 m was 1.22 mm/d (0.0479 in/d) and 1.20 mm/d (0.0472 in/d), respectively. As such, there was no statistically significant difference in leakage rates between the two categories of EMS.

CONCLUSIONS

Commercially marketed diaphragm–type water–level sensors were not sufficiently sensitive to measure small short–term water–level fluctuations in EMS. The siphon and balance system developed for this project provided sufficient sensitivity to detect water level fluctuations as small as 0.012 mm, which is less than 1% of the maximum daily leakage allowed by Iowa regulations.

Small errors in measurement of precipitation, EMS liquid levels, and evaporation can seriously affect leakage estimates derived using water balance calculations. Leakage estimates were improved by basing them on data sequences collected during periods characterized by zero precipitation, peak wind speeds <3 m/s, and relative humidity >90%.

Whole–basin leakage determinations were successfully made at slightly more than 6% of the 439 EMS constructed in Iowa between 1 January 1987 and 31 December 1994. Of 28 sites tested, only one (less than 4%) had a leakage rate significantly ($p < 0.05$) higher than the maximum (1.6 mm/d at 1.8 m liquid depth) allowed by Iowa regulations at the time that the structures were built. Forty–three percent of the sites had leakage rates statistically lower than the regulatory limit, and leakage at the remaining 53% of sites was not statistically different from the regulatory limit. Mean leakage rates for EMS constructed in glacial till soils were significantly lower than for structures constructed in loess, colluvium, or sand and gravel. No statistically significant differences in leakage rates were observed between sites where loess, colluvium, or sand and gravel are the dominant surficial materials. When plotted against structure age, estimated leakage from the 3 to 11 yr old structures displays considerable scatter, but the slope of the regression line (–0.16 mm d^{-1} yr^{-1}) is significantly different from zero. Despite the much higher solids content of liquids in slurry pits, mean leakage rates for 15 slurry pits and 12 lagoons were not significantly different.

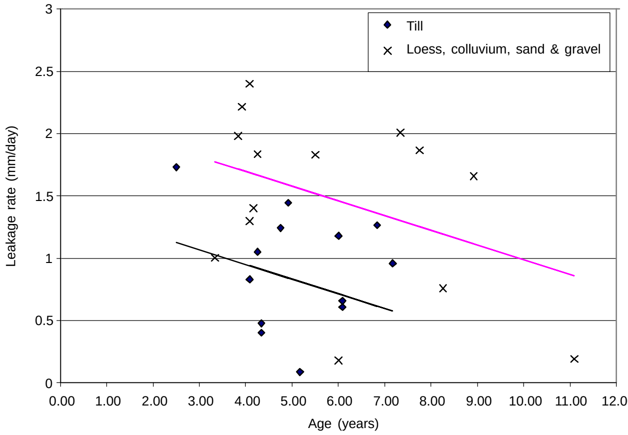

Figure 5. Mean leakage rate (at 1.8 m liquid depth) versus structure age for earthen manure structures constructed in till and non–till (sand and gravel, colluvium, loess) materials.

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