Measurement of Seepage from Earthen Waste Storage Structures in Iowa

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ABSTRACT

In 1997 the Iowa legislature mandated that Iowa State University conduct a statewide study of point and nonpoint pollution caused by earthen waste storage structures. As one indicator of environmental impact, researchers measured seepage in a representative sample of 28 earthen structures located within five aquifer vulnerability regions of the state. Study sites were instrumented to measure liquid levels, pan evaporation, rainfall, wind speed and direction, air temperature, and relative humidity at two-minute intervals during a 3 to10 day period during which no liquid was discharged into or out of the structures. Statistical analysis of the data indicates that 43% of the tested structures had seepage rates significantly (with 95% confidence) lower than the regulatory standard of 0.0625 inches/day (at six-foot liquid depth) specified by the State of Iowa at the time the basins were constructed. Earthen structures included in the study had been in service from 2.5 to 11.1 years. Regression analysis failed to confirm significant age-related trends in seepage for structures within the age range covered by this study. When grouped by general type of dominant geologic surficial material, structures located within glacial till have significantly lower seepage rates than those constructed at sites where sand and gravel, colluvium, or loess is the dominant surficial material. Comparison of slurry pits and lagoons showed no significant differences in seepage rate.

During the spring of 1997 the Iowa Legislature passed a bill mandating Iowa State University to conduct a statewide study of water quality impacts caused by earthen waste storage structures (EWSS). Based on reviews of previous EWSS studies conducted in Iowa and other states, ISU researchers concluded that statewide impacts of EWSS would be characterized most effectively through four coordinated subprojects designed to:

- measure whole-basin seepage at representative structures throughout Iowa and compare these values with State seepage regulations;
- examine soils in the vicinity of the tested structures for chemical evidence of seepage and contaminant migration;
- interview owners and/or operators of earthen structures to evaluate operation and maintenance practices that impact local water resources; and
- characterize the hydrogeologic settings of representative earthen structures using aerial photographs and published soils and topographic data, and evaluate the potential of the structures to affect water resources.

This report summarizes results of the seepage measurement study. Additional chapters in this report document the results of the other three phases of the project (Simpkins et al., chapter 1; Richard et al., chapter 2; Baker et al., chapter 4).

BACKGROUND

Due to their relatively low construction and maintenance costs, earthen waste storage structures have long been used for storage and treatment of municipal and industrial wastewater. Approximately 715 municipalities and semi-public entities in Iowa utilize earthen waste stabilization lagoons or aerated lagoons to store and treat wastewater. Following the lead of small municipalities and industries, many medium- and large-scale livestock producers have adapted earthen structures for storage and/or biological treatment of liquid manure.

The State of Iowa currently recognizes two types of earthen waste structures used for liquid animal manure. "Slurry pits" (also called "earthen basins") are used for short-term (typically 6 months) storage of undiluted manure prior to field application. Due to high concentrations of ammonia- and ammonium-nitrogen in undiluted manure, both of which are somewhat toxic to microorganisms, biological degradation of manure solids in slurry pits is relatively low. Volatilization of ammonia from manure stored in slurry pits can cause nitrogen losses of 15 to 30% depending on the rate of gas production and the amount of bedding and other floating organic material that is available to form a crust on top of the liquid. If additional biological treatment is desired manure is diluted with water and placed into earthen structures called “lagoons”. Conditions within the dilute manure favor growth of anaerobic microorganisms that decompose solids into ammonia, methane, carbon dioxide, and hydrogen sulfide. As decomposition occurs, 70-80% of the nitrogen is typically lost through ammonia volatilization. At the time this study was begun, the Iowa Department of Natural Resources

(IDNR) had granted operating permits to approximately 694 animal feeding operations. Of these, 602 were listed in the IDNR database as using earthen pits or lagoons as a component of their manure management system.

The impacts of EWSS on ground- and surface-water resources are not a new concern. In their 1983 survey of literature on seepage from earthen manure structures, Louden and Reece reviewed results of 22 studies that had been published between 1965 and 1982. A more recent review of research results and state regulations by Parker et al. (1994,1999) lists quantification of seepage rates, effects of soil type on seepage, and soil sealing effects of animal manure, as the three primary objectives of earthen structure research during the past 30 years.

The national trend toward large confined animal feeding operations has raised public concern about their potential environmental impacts, and has caused many state legislatures and environmental agencies to reassess their regulatory programs. 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 current 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 an effort to bolster federal assistance and regulatory programs, two federal agencies have recently initiated new programs. The U.S. Environmental Protection Agency (USEPA) has recently released its *Draft Strategy for Addressing Environmental and Public Health Impacts from Animal Feeding Operations* (USEPA, 1998) which is intended to be a “blueprint for a significant expansion of USEPA’s regulatory and voluntary efforts related to animal feeding operations.” Similarly, the Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture is providing additional technical guidance on design and construction of waste storage ponds and treatment lagoons through it’s new *Geotechnical, Design, and Construction Guidelines* appendix to its Agricultural Waste Management Field Handbook (Natural Resources Conservation Service, 1997).

Responding to policymakers and regulators seeking more definitive information on the magnitude, frequency, and impact of seepage from EWSS, new studies have been initiated in several states. Soil sampling and groundwater monitoring have been the most common methods used to evaluate earthen structure seepage. Soil samples collected down gradient from eleven 10-20 year old lagoons in North Carolina indicated that five lagoons exhibited low seepage, while the remaining six were judged to have moderate or high seepage. Elevated ammonium-nitrogen in the soil was the strongest indicator of seepage (Huffman and Westerman, 1995). Monitoring wells near two new swine lagoons constructed in deep sandy soils in North Carolina exhibited significant seepage after 3-5 years, and significant spatial variation of contaminants within the seepage plumes were considered indicative of localized seepage from certain areas of the lagoons (Westerman, et al., 1995). The North Carolina Division of Water Quality Groundwater Section (1998) used monitoring wells to test the usefulness of groundwater vulnerability criteria in assessing the pollution potential of 11 animal manure lagoons. Groundwater monitoring near five lagoons located at sites judged to be "less vulnerable" showed no evidence of seepage. Three of four lagoons at sites judged "moderately vulnerable" showed increasing trends in nitrate-nitrogen or chloride concentrations, and monitoring wells near one of two lagoons located within "vulnerable" sites contained ammonia, potassium, and nitrate-nitrogen thought to originate from the lagoon. Libra and Quade (1997) have reported results of several years of groundwater monitoring near four earthen manure structures located in differing geologic settings in Iowa.

Several recent earthen structure studies have employed methods other than groundwater monitoring or soil sampling. A dairy manure lagoon in Minnesota was constructed with a special underdrain system that permitted capture and direct measurement of seepage through portions of the bottom and sidewall. Results showed significantly greater seepage through the sidewall than the floor during the first year of operation. Sealing of the bottom by solids deposition, and differential sidewall and floor compaction efficiencies during construction, were believed to be the most likely causes for these results (Hetchler and Clanton, 1996; Swanberg, 1997).

Relatively few studies have attempted measurement of seepage in operational earthen structures. Most recently Ham and Desutter (1998) used a water balance method to determine seepage from three recently constructed swine-waste lagoons in Kansas. Seepage rates ranged from 0.02 to 0.075 inches/day.

RATIONALE & OBJECTIVES for SEEPAGE STUDY

To date relatively few studies have attempted to measure whole-basin seepage in active earthen waste storage structures. The more typical approach to investigating groundwater impacts has been through sampling of water from groundwater monitoring wells. The decision to undertake a seepage study as part of the legislatively-mandated study of earthen waste storage structures in Iowa was motivated by a variety of considerations. Key among these was the project scope and duration, as set forth by the Iowa Legislature. The stated scope was broad, calling for a statewide assessment of point and nonpoint pollution caused by earthen waste storage structures. At the same time, the project duration was to be relatively brief. Results were to be reported to the legislature within 18 months.

With these project constraints in mind, installation and long-term monitoring of groundwater monitoring wells, the most common approach to this type of study, were ruled out. Groundwater monitoring efforts can easily take several years to complete, particularly if leakage is localized and difficult to locate, or contaminant migration rates are low.

With more than 600 agricultural basins located in a broad variety of geologic and topographic settings throughout Iowa, it became particularly important to identify indices of pollution potential that could be evaluated quickly at a sufficient number of sites to be representative of statewide conditions.

After due consideration, whole-basin seepage measurements were judged worthy of further work since they appeared to offer a variety of potential benefits. These include:

- rapid assessment…..it was believed that whole basin seepage measurements could be made at a study site in 3-10 days given favorable weather conditions (low wind and minimal rainfall);
- regulatory relevance…. whole-basin seepage measurements can be directly compared with state regulatory limits on earthen structure seepage;
- localized seepage can sometimes be difficult to detect using monitoring wells, but whole-basin measurements can quantify seepage without actually having to locate the structural defect;
- environmental impact assessment…..the annual mass of nutrients transported into the soil with seepage can be estimated by multiplying nutrient concentrations in the basin liquid by the predicted annual seepage; and
- future utility to the State of Iowa…..if seepage measurement techniques can be perfected, this would offer a potentially useful evaluation tool for periodic monitoring of earthen structures.

With the forgoing project goals in mind, specific project objectives for the seepage measurement portion of the overall research were reduced to the following:

- develop and test field seepage measurement techniques using off-the-shelf data collection and logging equipment;
- develop data analysis techniques for reducing weather and water-level data to seepage estimates;
- test the above techniques on approximately 10% of EWSS in the IDNR's electronic database of livestock facilities that obtained permits during the years from 1987 through 1994.

SITE SELECTION

As previously noted, some of the more recent earthen structure research suggests that natural processes may lead to increased seepage (primarily through the sidewall) with time. Potential aging factors include: sidewall cracking, caused by freezing and thawing or desiccation; penetration by roots and earthworms or rodents; erosion, caused by rainfall and wave action, poorly protected inlets, and improper agitation during pumping; and liner collapse due to external pressure and groundwater intrusion.

Based on the potential impacts of aging on seepage rates, and the fact that soil and groundwater contamination can take several years to migrate sufficiently far from a structure to be detected, the ISU project team concluded that study sites should be at least three years old. By focusing on structures that had been in service for several years, project planners hoped to evaluate the full range of long-term impacts on local water resources.

The Iowa Department of Natural Resources electronic database of permitted livestock facilities was used to identify potential study sites. A database query identified 439 facilities constructed during the period from 1/1/87 through 12/31/94. Facility owners were contacted by mail and invited to participate in the project. Potential cooperators were asked to fill out a questionnaire providing background information that would aid final site selection. Response to the call for participants was extremely good with 124 EWSS owners responding favorably.

To achieve the goal of testing a representative sample of approximately 10% of the target population, 40 earthen manure basins and lagoons was selected for the study so that the ratio of basins to lagoons was similar to that in the total population. Since assessment of impacts on groundwater was a key objective of the legislatively-mandated study, groundwater vulnerability also was a key criterion for site selection. Using Iowa's groundwater vulnerability map (Hoyer and Hallberg, 1991) project geologists identified five major aquifer vulnerability regions. These include areas underlain by surficial aquifers (alluvial or drift); and regions where confined aquifers are overlain by thin drift (less than 100 ft thick), moderate drift (100-300 ft thick), or shale. Here again, study sites were selected so that the proportion in each of the vulnerability regions was similar to that in the total population of earthen structures.

Of 40 sites selected for participation, owners of five structures ultimately failed to sign a memorandum of understanding with ISU permitting project staff to enter their property. Of the remaining 35 sites one was ultimately found to have been abandoned and filled in. Further site investigation revealed that liquid levels at four sites were below the surrounding ground elevation. Since excavation would have been necessary to monitor these structures, they were dropped from the study. A considerable body of monitoring data also was collected on an ISU research farm during field testing of monitoring instruments. Although the earthen structure did not meet the three-year minimum age criterion, these data were added to the project results, bringing the total number of sites monitored for seepage to 31.

FIELD MEASUREMENTS AND DATA ANALYSIS

Instrumentation and Data Collection

At the time planning for the seepage measurement project was begun, Iowa regulations specified a maximum seepage rate of 1/16 inch per day (0.0052 ft/day) at a liquid depth of 6 feet. To determine if commercially available transducers could reliably measure such small fluctuations in liquid level, the ISU project team reviewed scientific literature relevant to a variety of research projects where small changes in water level were necessary. Manufacturers or vendors of water-level monitoring devices (Campbell Scientific, Druck Incorporated, Kobold Instruments) also were consulted. Based on these investigations, it was concluded that the most sensitive water level sensors readily available at a reasonable cost were designed to monitor water level fluctuations over a range of 2 - 5 feet. With advertised full-scale accuracies of 0.1%, these devices were only capable of detecting water level fluctuations of 0.002 feet or greater, and these capabilities were further qualified by manufacturer's application guidelines specifying that the devices be used in "clean" water to avoid plugging and other operational problems.

Since it was anticipated that some basins would exhibit seepage rates less than the regulatory maximum, it was desirable to find instrumentation capable of detecting water level fluctuations considerably smaller than 0.002 ft/day. Furthermore, it was quite clear that whatever system was employed, it would need to be able to function in liquids other than clean water. Lacking knowledge of, or ready access to, a suitable commercial system, the research team proceeded with design and testing of custom-designed instrumentation that could meet project requirements.

The specially designed system illustrated in figure 1 was conceived and field-tested in the spring of 1998 by ISU researchers. This system employs a siphon tube that provides a hydraulic connection between liquid in the earthen structure and water in a beaker located on a portable electronic balance that is housed inside an instrument cabinet (figure 2). Liquid-level fluctuations within the basin are transmitted through the siphon tube, producing fluctuations of equal magnitude within the beaker. The diameter of the beaker dictates the sensitivity of this system. For the setup employed in the study, a 1-millimeter (mm) rise in liquid level causes an 8-gram increase in the mass of water inside the beaker. Since the electronic balances are capable of reliably detecting mass changes as small as 0.1 gram, the liquid level monitoring system is theoretically capable of detecting water level changes of 0.0125 mm. In practical application, the system more realistically detects fluctuations of 0.0250 mm which is equivalent to less than 0.0001 ft. As such, the sensitivity of this instrumentation is approximately 20 times greater than that offered by commercial water level sensors readily available at the time the project was begun.

In addition to logging water level fluctuations inside the earthen structures over a period of 3-10 days, each monitoring site was equipped with a tipping bucket rain gage and apparatus for measuring wind speed and direction, air temperature, and relative humidity. These data were collected using commercially available weather instruments. In addition, a second siphon tube and balance system was used to measure evaporation from a 22-inch diameter evaporation pan located on the outside of the berm (figure 3).

Seepage Determination

Several processes cause liquid level fluctuations within an earthen structure. These include liquid inputs, such as rainfall and pumping into the structure; and liquid outputs, which include evaporation, seepage, and pumped withdrawals.

The interrelationships of these factors can be described by the general water balance formula:

Inputs - Outputs = Change in storage

By agreement with the cooperating facility owners, pumping into and out of the EWSS was curtailed during seepage monitoring. With these inputs and outputs eliminated, the water balance relationship becomes:

$$\underset{\uparrow\ \text{Input}}{\textit{Precipitation(cm/day)}}-\underset{\uparrow\ \text{Outputs}}{\textit{[Evaporation(cm/day)+Seepage(cm/day)]}} = \textit{Liquid level change(cm/day)}$$

Although seepage is labeled as an "output" here, seepage into an EWSS will occur whenever the elevation of the local groundwater table rises above the liquid inside an earthen structure. Evaluations of hydrogeologic settings of the EWSS in this study indicate that the floors of a large percentage are probably below seasonally high water tables (Simpkins et al., chapter 1 of this report). At the time seepage monitoring was conducted, however, liquid levels in the study structures were approaching design depth. When compared with water levels observed in soil core holes near the structures, interior liquid levels at all sites appeared to be at or above the local water table.

By further restricting measurement of liquid level changes to time periods when no precipitation occurs, precipitation can be dropped from this equation. Through algebraic reorganization of the three remaining terms, the formula shows that the rate of seepage can be calculated by subtracting the evaporation rate from the rate of liquid level change.

Seepage rate = Rate of liquid level change - Evaporation rate

To further illustrate how the water balance equation is applied, figure 4 shows a sample of liquid level data collected at one of the earthen structures tested during the ISU seepage study. The linear regression line drawn through the data shows that the liquid level declined approximately 1.6 mm (0.0394 inches) during the 8-hour period from midnight to 8:00 AM. When extrapolated to a 24-hour basis, the estimated rate of liquid level decline is 4.8 mm/day (0.1890 inches/day). Evaporation measurements during the same time period indicate an evaporation rate of about 0.4 mm/day (0.0157 inches/day). Subtracting this rate of evaporation from the rate of liquid level decline, the seepage rate is calculated to be 4.4

mm/day (0.1733 inches/day). Under favorable weather conditions, several data sequences were collected at each site, and the mean value (converted to units of inches per day, to be dimensionally consistent with Iowa's seepage regulations) was used as the best estimate of seepage.

Wind effects are a major cause of variability in measurements of whole-basin seepage. Sudden changes in wind speed or wind direction can cause short-term fluctuations in liquid levels that obliterate the subtle effects of seepage and evaporation. Examples include "wind setup," a phenomenon observed when wind-driven water piles up along the downwind shoreline of a body of water. When this occurs, a gradual increase in liquid levels will be observed at downwind monitoring stations although no liquid is being added to the structure. Even at wind speeds too low to cause wind setup, surface waves of varying velocity and amplitude can create oscillating water levels that must be identified and removed from the data stream before the effects of seepage and evaporation can be quantified.

To illustrate some of the complications caused by wind-induced waves, the sample data in figure 5 show relatively minor (less than 1 mm) liquid level oscillations caused by average wind speeds of only 1.5 meters/second (3.35 miles/hour). Despite these wind effects, the regression line through the data show that liquid fluctuations caused by waves are superimposed over a gradually declining trend line indicating a constant liquid level decline at a rate of nearly 0.6 mm/day (0.0236 inches/day). Data collected at another time, under different conditions of wind, temperature, relative humidity, and other factors will yield slightly different estimates of liquid level decline. This variability is inevitable when collecting data under field conditions where external influences cannot be fully controlled.

Because wind and other uncontrolled influences can play such a crucial role in the measurement of minute liquid level fluctuations, realistic assessment of seepage must recognize the variability caused by these factors. Although results of several measurements can be averaged to obtain a single estimate of seepage at each study site, this average value is only an estimate of the "true value" which realistically lies somewhere within a range of values. To reflect this reality, figures 6 and 7 in the "Results" section of this report show both a mean value and a 95% confidence interval for the mean. The confidence interval illustrates the range that is 95% likely to contain the true seepage value.

Readers will note that some sites have broader 95% confidence intervals than others. 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 several useful nighttime data sequences. Under less favorable conditions, only one or two useful data sequences were obtained. Since larger amounts of data permit a better estimate of the mean value, the likely range of values is smaller for sites with more data. Statistical analysis also revealed that data variability was not uniform across the study sites, but instead is proportional to the estimated value of the mean loss rate for each site. As a result, sites with higher estimated mean loss rates tend to have broader 95% confidence intervals.

Evaporation Determination

As noted earlier, evaporation data were collected by measuring the rate of water level decline within an evaporation pan installed at each study site. Pan measurements are a common method for approximating evaporation from large, open bodies of water, but it is widely recognized that pan data often overestimate the true rate of evaporation from ponds and lakes. Differences between lake and pan conditions that can bias the pan data include (Burman and Pochop, 1994):

- differing water temperature variations with depth;
- storage of heat within the pan;
- differences in wind exposure;
- differences in the turbulence, temperature, and humidity of air above the water surface; and
- heat transfer through the sides and bottom of the pan.

Since pan evaporation normally exceeds evaporative losses from larger water bodies, researchers commonly adjust the pan data to obtain a more realistic estimate of lake evaporation. Adjustment is accomplished by multiplying pan data by a "pan coefficient," which is the ratio of lake or reservoir evaporation to the evaporation indicated by pan data. Typical pan coefficients range from 0.7 to 0.9 (Brutsaert, 1982) depending on the pan and its surrounding environment.

In the special case of evaporation of liquid from earthen structures containing livestock manure, selecting an appropriate pan coefficient is further complicated by two additional factors. In some instances livestock waste forms a floating scum layer that reduces the exposure of the liquid surface to wind and solar energy. When present, this layer impedes water transfer to the atmosphere, increasing the difference between pan evaporation and actual evaporative loss from an EWSS. Elevated salt concentrations, which are typical in liquid animal wastes, also may suppress evaporation to a limited extent. This effect appears to be minor, however, as studies of evaporation from saline lakes and reservoirs in western states (Harbeck, 1955) indicate that suppression does not become significant until salinity levels are much higher than typically found in liquid manure.

Preliminary evaluation of evaporation pan data and liquid level data within the earthen structures showed that daytime pan and EWSS evaporation losses can be considerably higher than those observed at night. In some instances pan measurements over-estimated evaporation to the extent that the evaporative loss exceeded the basin loss measurements (which include seepage and evaporation). Overestimation of evaporation causes the water balance equation described earlier to predict negative seepage rates, implying net seepage into the structure rather than out of it. As noted earlier, however, seepage monitoring was conducted at a time of year when most EWSS were approaching design depth. When compared with water levels observed in soil core holes located near the structures, interior liquid levels at all sites appeared to be at or above the local water table, thereby precluding the possibility of groundwater seepage into the structures.

Even when daytime pan losses did not exceed the measured basin loss, evaporative losses were sometimes sufficiently large to interfere with seepage calculations. When estimated evaporation rates are large, even relatively small errors can lead to large errors in the seepage estimate. In some instances, underestimation of daytime evaporation (probably caused by high winds) resulted in preliminary seepage estimates that exceeded the estimated daily discharge from the livestock facilities. Since continuous seepage rates of this magnitude would preclude an earthen structure from filling, preliminary results of this nature initiated a review of data analysis methods.

To further reduce the potential for error in determining seepage, a revised data analysis strategy was devised. Since wind and evaporation are the two factors that interfere most with field measurements of seepage and liquid level fluctuations, the revised procedure uses only data collected at times when evaporation rates and wind speed are minimal. To accomplish this, a computer program was written to scan data at each study site and select data sequences when relative humidity exceeded 90%, maximum wind speed was less than 3 meters/second, and no precipitation occurred.

This "filtering" strategy typically identifies data sequences collected at night and/or in the early morning, ideal times in the sense that solar energy is non-existent or very low, and wind velocities are typically low. Furthermore, nighttime air temperatures also are normally lower than during the day. This leads to cooling of water surfaces, another factor in reduced evaporation. Cooler nighttime conditions also favor increased humidity levels and, as humidity increases, the amount of additional moisture that air can hold decreases, further suppressing evaporation.

Analysis of nighttime pan data produced useful evaporation data for about 60% of the basin loss measurements made during the study. Wind interference prevented acquisition of acceptable data at other times. The successful evaporation determinations had an overall mean value of 0.56 mm/day (0.0216 inches/day) and a standard deviation of 0.43 mm/day (0.0169 inches/day).

Since about 40% of the basin loss data (the measured decline in liquid level within an EWSS) lacked concurrent evaporation data necessary for seepage determinations, several alternative sources of evaporation data were considered. Since all evaporation data were collected under similar atmospheric conditions (relative humidities exceeding 90% and peak wind less than 3 meters/sec) one approach considered was to apply a pan coefficient to the mean of all the successful evaporation determinations and use this estimate for all sites. Applying typical pan coefficients of 0.7 to 0.9 to the mean evaporation yields nighttime estimated EWSS evaporation ranging from 0.39 to 0.50 mm/day (0.0153 - 0.0199 inches/day).

Since meteorologists and hydrologists are often faced with making evaporation estimates based on relatively scarce meteorological data, a variety of evaporation prediction equations have been developed. One of the more common formulas reported by Dingman (1994) is:

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

where E is the predicted evaporation rate (cm/day);
K_E is a mass transfer coefficient of approximately 1.26×10^{-4} (sec/mb-day)
ν_a is measured wind speed (cm/sec); and
ρ_s and ρ_a are vapor pressures measured in millibars (mb) at the liquid surface and in the air (calculated based on temperature and relative humidity measurements)

At air temperatures ranging from 10 to 20 °C, average wind speeds of 1.5 to 2.0 meter/second, and a relative humidity of 95%, evaporation rates in the range of 0.15 to 0.35 mm/day are predicted by this formula. These predictions agree reasonably well with the previously discussed coefficient-adjusted mean evaporation rates of 0.39 - 0.50 mm/day. Furthermore, since evaporation from EWSS may be suppressed further by the effects of floating debris, the true nighttime evaporation rate may be as low as 0.1 to 0.2 mm/day (0.0039 - 0.0079 inches/day).

PROJECT RESULTS

Perspectives on the Data

Evaporation Considerations. From a scientific standpoint evaporative losses are very important when using a mass balance approach to determine seepage and, as previously discussed, evaporation has received careful consideration in this study. As noted earlier, however, evaporation and seepage calculations presented in this study are based on data collected at times (typically at night) when evaporation is estimated to be only 0.2 to 0.3 mm/day. In most instances this is less than the inherent variability of the liquid level fluctuation data, as illustrated by the 95% confidence intervals shown in figures 6 and 7. From a practical standpoint then, correcting liquid level data for evaporation does not significantly improve the accuracy of seepage estimates. With this in mind, evaporation corrections have not been applied and statistical comparisons presented in this section are based on measurements of total liquid loss rates (i.e. seepage plus evaporation). Consistent with this approach, the data shown graphically in figures 6 and 7 are slight overestimates of seepage and are referred to as "liquid loss" to distinguish them from true seepage.

Background on Regulatory Seepage Limits. At the time the study basins were constructed (1987-1994), Iowa's EWSS regulations permitted 1/16th inch (0.0625 inches) of seepage per day at a liquid depth of 6 feet. Early in 1999, the IDNR adopted new rules limiting maximum seepage in new earthen structures to 1/16th inch/day when filled to design depth (maximum allowable depth). Although the quantity of allowable daily seepage is the same, the new rule is considerably more stringent due to the increased regulatory depth at which it applies and the fact that maximum seepage from an earthen structure occurs at maximum liquid depth.

Before comparing data from this study with Iowa's regulatory seepage limits, it should be noted that the whole-basin seepage measurement methodology devised especially for this project differs in both timing and technique from the methods normally employed to substantiate regulatory compliance. Current regulations require proof of compliance to be submitted prior to start-up of new earthen structures. As such, Iowa's seepage regulations are used primarily to evaluate new construction, as opposed to performance monitoring of structures already in service. Furthermore, seepage tests for regulatory purposes are generally conducted in the laboratory on small cores extracted from the floor and sidewalls. Whole-basin measurements, as the name implies, test a major portion of the structure if conducted when a lagoon or basin is nearly full. Recognizing these fundamental differences in seepage measurement methods, whole-basin measurements that fail to meet current or past seepage limits do not necessarily imply that a structure failed to meet state requirements at the time of construction.

Estimating Losses at Past and Current Regulatory Depths. Field seepage measurements were obtained during late summer or fall as liquid depths approached design depth. Of the 28 study sites for which loss rates have been estimated, nearly 80% were filled to within three feet or less of design depth. Since seepage rates increase with increasing liquid depths, field measurements must be adjusted to be comparable with regulatory seepage limits at six-feet or design depth. Adjustment to a common depth also is necessary to make meaningful comparisons between structures or to evaluate seepage trends with age or other physical factors. Figure 6 charts estimated liquid loss rates at a liquid depth of 6 feet (depth specified by Iowa seepage regulations prior to 1999), while figure 7 shows estimated loss rates when structures are filled to design depth (depth specified in Iowa's current seepage regulations).

Field measurements were converted to estimated loss rates at design depth and six feet using Darcy's law, a relationship that predicts the velocity of flow through soil or other porous media based on the material's hydraulic conductivity and on the hydraulic gradient across the material. Darcy's law is described by the equation:

$$V = KI$$

where

V= velocity of flow;
K= hydraulic conductivity;
I = hydraulic gradient.

For the purposes of estimating flow rates through the compacted soil liner of an EWSS, hydraulic gradient is defined by the equation:

$$I = H/L$$

where

H = hydraulic head loss across the soil liner of the EWSS; and

L = thickness of the soil liner.

Head loss (H) across the soil liner is defined by:

$$H = D+L-h$$

where

D = depth of liquid in EWSS;

L = thickness of compacted soil liner; and

h = hydraulic head beneath the soil liner.

If the soil liner has uniform hydraulic conductivity and thickness throughout the structure, the seepage rate (V_2) at any desired head loss (H_2) can be estimated from field measurements of seepage (V_1) made at a known head loss (H_1) using:

$$V_2 = V_1 [H_2/H_1]$$

Due to project time limitations, depth-adjusted seepage rates in this report are based on liquid depth (D) and liner thickness (L). Sufficient field data were not available to reliably determine h. Structures were surveyed to determine liquid levels (with respect to the top of the berm) at the time seepage monitoring was conducted. The distance from the liquid level to the top of the berm was subtracted from the total height of the structure (bottom to top of berm height) reported by the owner or manager to determine liquid depth. Liner thickness, which constitutes only a small fraction of H, was assumed to be one foot.

Assessment of local water table elevations, an important factor in determining the third component (h) of total head (H), was limited, due to time constraints, to single observations. These were made in eight-foot deep holes created when soil core samples were extracted at eight locations around the outer toe of the EWSS. At slightly more than one-third of the study sites, a water table was not intersected by the eight-foot core holes at the time of observation. In addition to their depth limitation, the one-time core hole observations do not portray seasonal changes in groundwater elevations or the effects caused by cyclical fluctuations of liquid levels within the EWSS. Longer-term studies, using monitoring wells constructed at greater depths, would be necessary to assess the full range of seasonal water table fluctuations.

Though a lack of complete water table data causes some error when estimating seepage rates at the past and current regulatory depths, these errors are well understood and do not prevent useful interpretation of the results. Some typical examples are the easiest way to clarify this. When a water table is present above the bottom of the soil liner, this condition reduces the total head across the soil liner. Failure to include this reduction results in overestimation of seepage rates for liquid depths less than the original depth (H_1). Consider an earthen structure that is located totally above the water table and has a liner thickness of 1 foot. If, this structure exhibits a seepage rate (V_1) of 0.1 inches/day when measured in the field at a liquid depth of 13 feet, then the head loss (H_1) for this condition is 14 feet. The same structure operating at a liquid depth of six feet would experience head loss of seven feet, and the estimated seepage rate ($V_2 = V_1$ [7/14]) is 0.05 inches/day. Under the same two liquid depth conditions, but with a constant water table 4 feet above the bottom of the soil liner, H_1 becomes 10 feet, H_2 is 3 feet, and the estimate for V_2 is ($V_2 = V_1$ [3/10]) 0.03 inches/day. In this case, failure to consider the effects of a water table leads to an estimate of V_2 that is 1.67 times greater than the true value in those cases when such a water table condition is present. This pattern of overestimation always holds true (if the water table elevation remains constant) when estimating V_2 at liquid depths less than the depth at which V_1 was originally measured. In situations where H_2 is not constant but decreases as the depth of liquid inside the structure decreases, the degree of overestimation is reduced.

The opposite occurs when converting field measurements to estimated seepage rates at depths greater than H_1. If the earthen structure in the previous example has a design depth of 15 feet (the average design depth for the structures monitored in this study), then the estimated seepage rate (ignoring a water table if present) at design depth would be 0.11 inches/day (V_1 [16/14]). As before, with a water table 4 feet above the bottom of the soil liner the estimated full-depth seepage rate is 0.12 inches/day (V_1 [12/10]). Here, failure to consider a water table leads to underestimates of V_2. As before, in situations where the height of the water table is influenced by the liquid level within the structure, then the degree of underestimation of seepage that results from failure to consider the water table is reduced.

Regardless of whether field measurements of seepage are being adjusted to greater or lesser depths, as the difference between H_1 and H_2 increases, so do the errors introduced by missing or inaccurate water table elevation data. Since seepage monitoring at most research sites was done at a time when liquid depths were approaching design depth, this means that estimated seepage at the six-foot regulatory depth should have the greatest error. Since failure to include water table effects lead to overestimation of seepage rates at reduced depths, the data in figure 6 are high, and the proportion of study sites that meet the former state seepage regulation (1/16 inch/day at 6-foot liquid depth) is somewhat understated. At the same time, the seepage estimates for design depth shown in figure 7 are underestimates for those situations where a water table exists above the bottom of the soil liner. Since field measurements for most sites were made when liquid depths were close to design depth, however, the degree of underestimation is often quite small, as illustrated by the previous example. As a result, the proportion of sites estimated to be meeting the current seepage regulation may be slightly overstated.

Comparisons with Former and Current Seepage Regulations

Former Regulatory Limit. Figure 6 shows estimated liquid loss rates when EWSS contain six feet of liquid (matching the former regulatory seepage limit). To determine whether a site is significantly above or below the former regulatory seepage limit, a one-sided statistical hypothesis test was conducted. Results of this procedure indicate that 12 of 28 sites (43%) have loss rates significantly ($p < 5\%$) less than the regulatory limit. The same type of statistical test indicates that only one site is significantly above the seepage limit. Loss rates at the remaining 15 sites are quite close to the $1/16^{th}$ inch/day regulatory limit and are neither significantly larger nor significantly smaller than the limit. Recognizing that the data in figure 6 are overestimates of true seepage (due to inclusion of evaporation at all sites, and possible water table effects at some sites), the true number of sites meeting the seepage limit may be more than the 43% cited above.

Current Regulatory Limit. Figure 7 displays loss rates adjusted to reflect conditions when EWSS are filled to the design depth (matching the recent change in Iowa's regulatory seepage limit). Since design depths for the study sites ranged from 6 to 32 feet (average of 15 feet), estimated design depth loss rates for deep basins can be several times the loss rate at 6 feet of liquid depth. Figure 7 displays data in the same basin order as shown in figure 6, making it possible to compare predicted loss rates at six feet and full depth for the same basin.

As before, statistical tests were conducted to estimate the likely number of study sites that meet the current seepage limit. Results indicate that four sites (15%) have loss rates significantly less than the new seepage limit ($p < 5\%$), while ten sites (36%) appear to have loss rates significantly greater than the seepage limit. The remaining 14 sites have loss rates sufficiently close to the seepage limit that one cannot say, with 95% confidence that they are either significantly less than or greater than the limit. Like the data in figure 6, small amounts of evaporation included in figure 7 lead to slight overestimation of seepage. For earthen structures that are consistently influenced by water tables, however, the previously described lack of water table data creates a concurrent tendency toward slight underestimation of seepage at design depth that, in part, offsets overestimates caused by evaporation.

Analysis of Potential Factors Affecting Seepage

In their recent overview of research results and state regulations relating to earthen structures, Parker et al. (1999) note that long-term effects of manure sealing, soil type, and climatological factors on seepage are yet to be fully understood. Though seepage rates in fine-grained soils are typically lower than in coarse-grained materials, this trend has apparently not been universal. Similarly, experiments designed to evaluate soil sealing mechanisms of animal manure have demonstrated seal formation in some cases and not in others.

To evaluate siting and design factors that may affect long-term seepage from earthen structures in Iowa, mean seepage values were statistically tested for evidence of trends with age, soil type, and manure type (pit versus lagoon). So that seepage rates from all structures are comparable, seepage estimates at a uniform liquid depth of six feet are used in these tests.

It should be noted that data from only 27 sites are used in the following trend analyses. Data from the site with the highest mean seepage (roughly three times greater than at any other site) have been omitted. While the seepage estimate for this site is considered to be valid, the abnormally high value suggests that this structure is affected by seepage mechanisms that are quite different from those affecting most basins. As such, the variability introduced by the large values at this structure makes it nearly impossible to draw statistical conclusions about more subtle differences in seepage among the other sites.

Relationship of Loss Rates to Soil Type. Based on soils data, topographic maps, and aerial photography, geologists participating in the ISU EWSS project classified each of the study sites according to their dominant surficial geologic materials (Simpkins et al., chapter 1 of this report). Ten materials groupings were originally identified but, since some included only one or two study sites, these were regrouped into four general surficial materials categories (note that these groupings differ from the five aquifer vulnerability regions originally used in site selection) for the purposes of this statistical analysis. The general categories include sand and gravel, colluvium, loess, and till.

As shown in figure 8, mean loss rates were highest at study sites where sand and gravel are the dominant surficial geologic material, and loss rates are lowest where glacial till dominates the site. Statistical analysis indicates that mean loss rates for till sites are significantly ($p < 5\%$) lower than mean loss rates for structures in the other three materials groupings. There is no statistically significant difference, however, among observed loss rates for sites where loess, colluvium, or sand and gravel are the dominant surficial geologic material.

Relationship of Loss Rates to Structure Age. One of the key questions concerning use of earthen structures is whether there is a sealing effect over time. Early thoughts on the subject suggested that EWSS filled with manure would "self seal" over time as deposited solids block pores or cracks in the floor or sidewalls. As noted in background information presented earlier, however, recent research also suggests that seepage through the sidewalls of earthen structures is greater than through the bottom. This suggests that natural processes such as freezing and thawing, wetting and drying, wave erosion, and intrusion by earthworms, roots, or rodents may lead to increased seepage as earthen structures age.

When loss rates are graphed versus age, the ISU data (figure 9) suggest a possible trend toward declining liquid loss rates with time. Two statistical approaches were used to test the significance of this apparent trend. In the first, linear regressions of loss-rate versus age were determined for each of the four major soil groupings. Since “till” and “non-till” sites were previously found to have significantly different loss rates, regression results for the three non-till groupings were pooled to obtain a single regression representing non-till sites. Subsequent statistical analysis showed that the slopes of the till and non-till regression lines were significantly ($p < 5\%$) different from zero, substantiating the likely existence of a relationship between age and loss rates. In the second method of analysis, the data were aggregated into “till” and “non-till” groupings, as shown in figure 9, before performing the regression analysis. Using this approach, the slopes of the till and non-till regression lines fell slightly short ($p = 0.0632$) of being significantly different from zero, indicating no significant trend with age. The inconsistent results of these two analytical approaches indicate that earthen structures in the 3 to 11 year age range represented by sites in this study are unlikely to exhibit significant trends in loss rate with age. Since this project was designed to examine structures that were at least three years old, no conclusions can be drawn regarding trends in seepage rate immediately following construction.

Comparison of Slurry Pits and Lagoons. Since slurry pits contain largely undiluted manure, the sealing potential for pits might reasonably be expected to be higher than for lagoons. Among the 12 lagoons and 15 slurry pits for which loss rates could be determined (excludes the single site with extreme seepage, as previously noted), mean loss rates at a uniform liquid depth of 6 feet were 0.0479 inches/day and 0.0472 inches/day respectively. As such, there was no significant difference in loss rates between the pits and lagoons tested in this study.

RECOMMENDATIONS

Results of this project suggest several possible courses of action for future consideration as Iowa's EWSS regulatory program continues to evolve.

While only one (3.6%) of 28 study sites clearly exceeded the previous seepage standard, 10 sites (36%) exceeded the more strict regulatory limit enacted in 1999. The higher failure rate under the more stringent rules points to a need for continued review and evolution of siting, design, and construction methods that can meet the revised seepage regulations.

Differences between loss rates for structures constructed in till, and for those located where sand and gravel, colluvium, or loess are the dominant surficial geologic materials, further emphasize the need for detailed siting, design, and construction guidelines that recognize differences in the performance potential of various soils and geologic materials. The recently revised *Geotechnical, Design, and Construction Guidelines* (NRCS, 1997), which use soil characteristics such as plasticity index and percent fines to help evaluate site suitability, may provide a useful starting point for continuing development of siting, design, and construction procedures that match varying soil conditions found throughout Iowa.

The lack of a clear-cut relationship between whole-basin seepage rates and structure age raises questions regarding how and when seepage should be measured to prove compliance with Iowa's seepage limit. Current rules describing Iowa's seepage limit for livestock lagoons and earthen basins mention collection and submission of seepage data only in the context of construction evaluation prior to start-up. This wording would seem to suggest that the regulatory limit is intended for evaluation of new construction only, and that it is not relevant to lifetime performance. The intent of the seepage rules should be clarified in this regard and, if applicable to lifetime performance monitoring, acceptable techniques (such as ground water monitoring, liner sampling and permeability testing, and/or whole-basin seepage testing) for evaluating seepage in operational structures should be articulated.

Much could be learned about long-term performance of EWSS through more intensive study of structures included in this study that have exhibited relatively high seepage losses. Monitoring of soil and groundwater beneath and around these structures could prove useful in developing site-specific, risk-based seepage and design guidelines that recognize important differences in pollution potential caused by variations in facility size and depth, waste strength, soil chemistry and permeability, and aquifer use and vulnerability.

Follow-up evaluation of temporal seepage variations in selected structures included in the ISU study also is recommended. Seepage measurements made at various liquid depth conditions during the operating cycle could help to pinpoint where leakage is taking place (floor, lower sidewall, upper sidewall) and to formulate design and construction methods that further reduce seepage potential.

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Many thanks also to Mr. Maxime Hunez, agricultural engineering student from France, who contributed many long hours in the field to this project during his undergraduate internship in the Department of Agricultural and Biosystems Engineering.

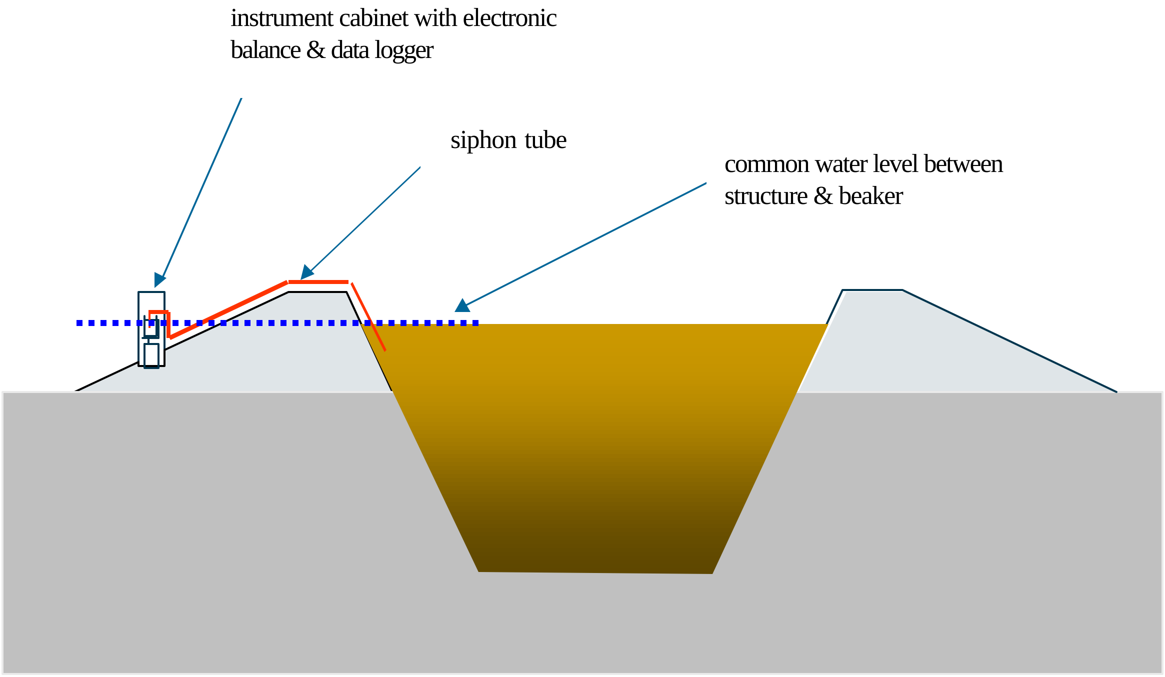

Figure 1. Schematic of water level measurement system using a siphon tube, battery-powered electronic balance, and data logger.

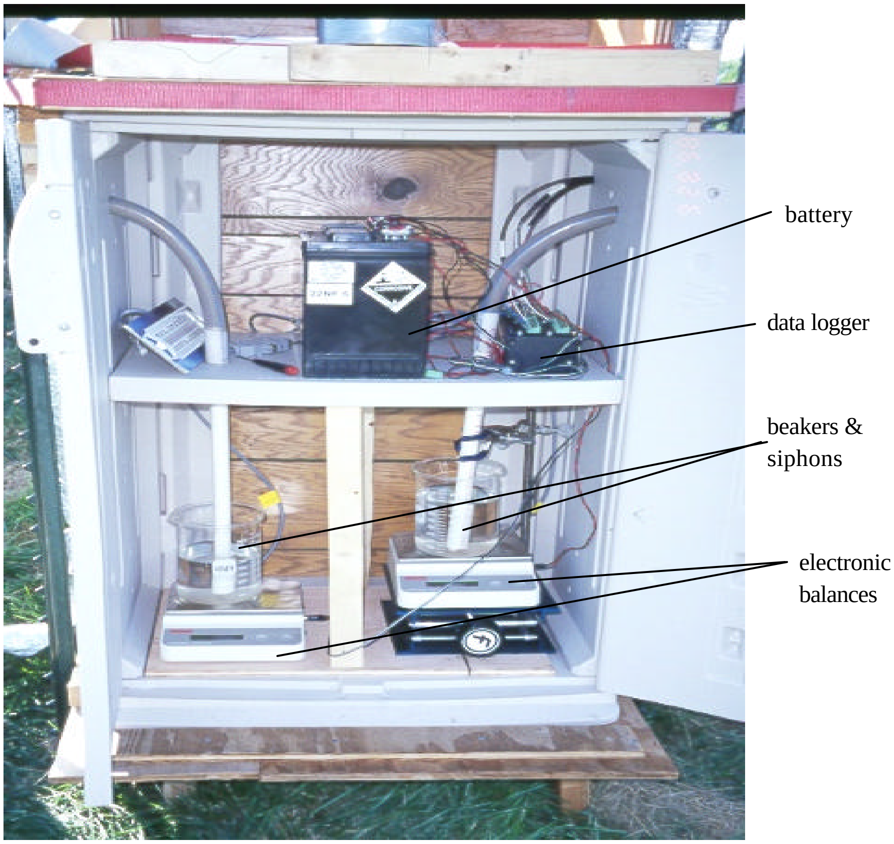

Figure 2. Electronic balances and data logging equipment used to record water level fluctuations within earthen structure and evaporation pan.

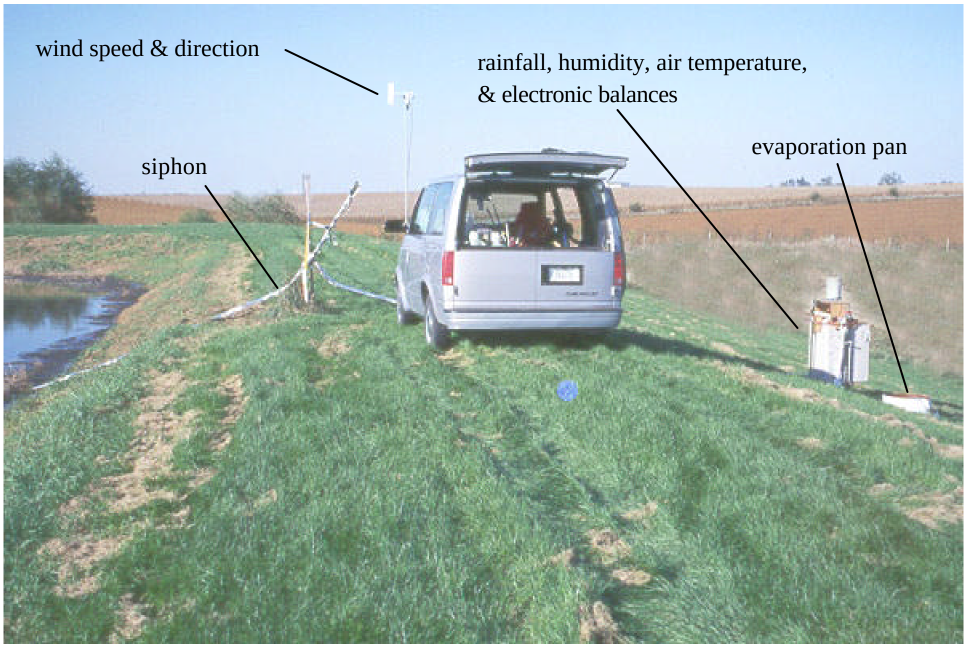

Figure 3. Typical liquid level and weather monitoring instrumentation at study sites.

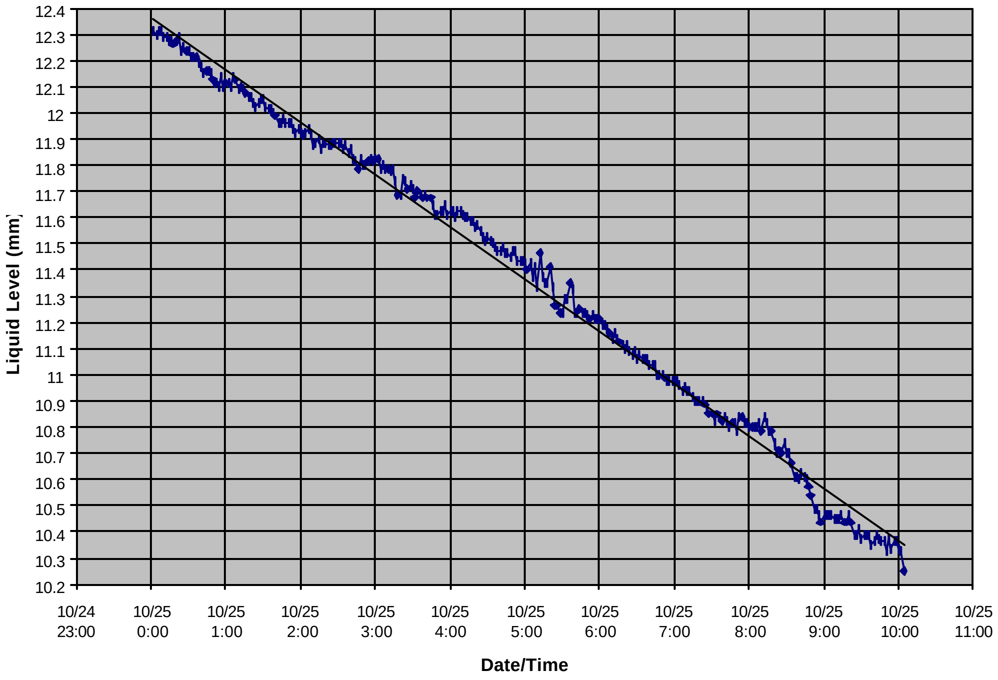

Figure 4. Sample data illustrating liquid level decline measurements under low wind conditions.

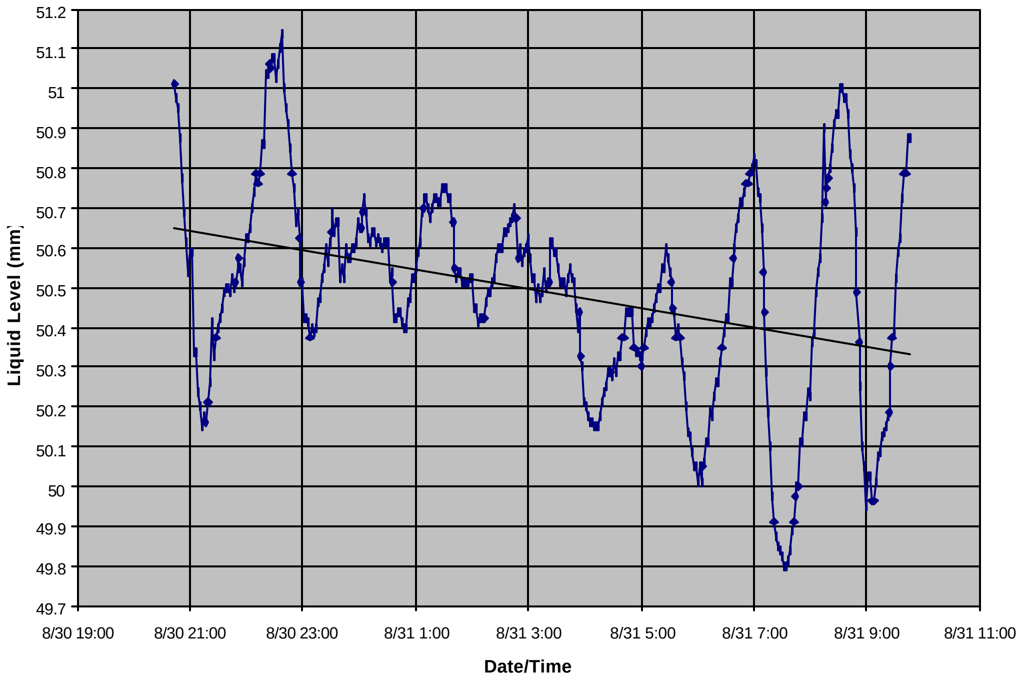

Figure 5. Sample data illustrating variability in liquid level decline data caused by wind-induced waves.

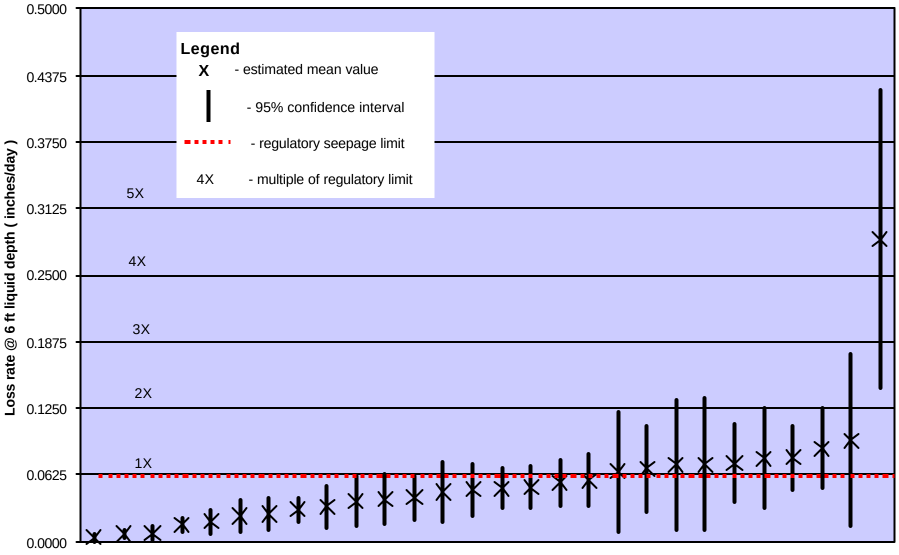

Figure 6. Estimated mean liquid loss rates and 95% confidence intervals for 28 EWSS at a liquid depth of 6 feet.

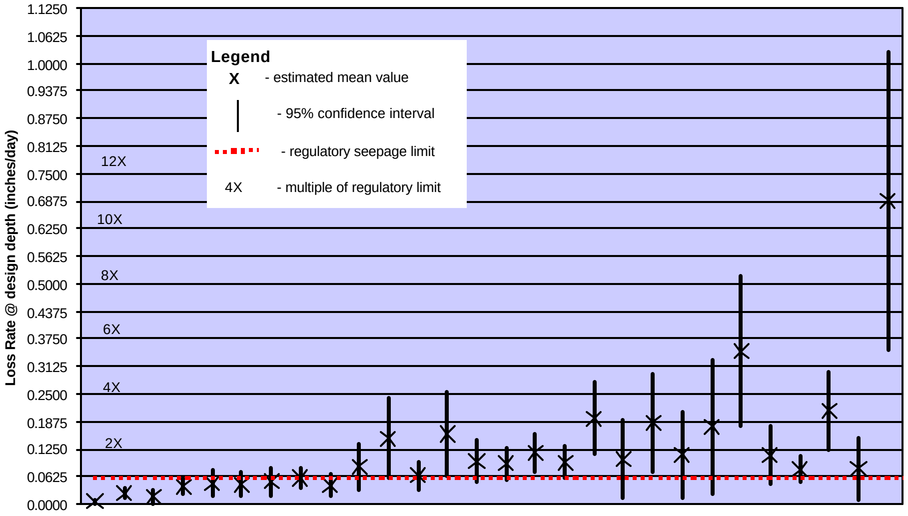

Figure 7. Estimated liquid loss rates and 95% confidence intervals for 28 EWSS filled to design depth.

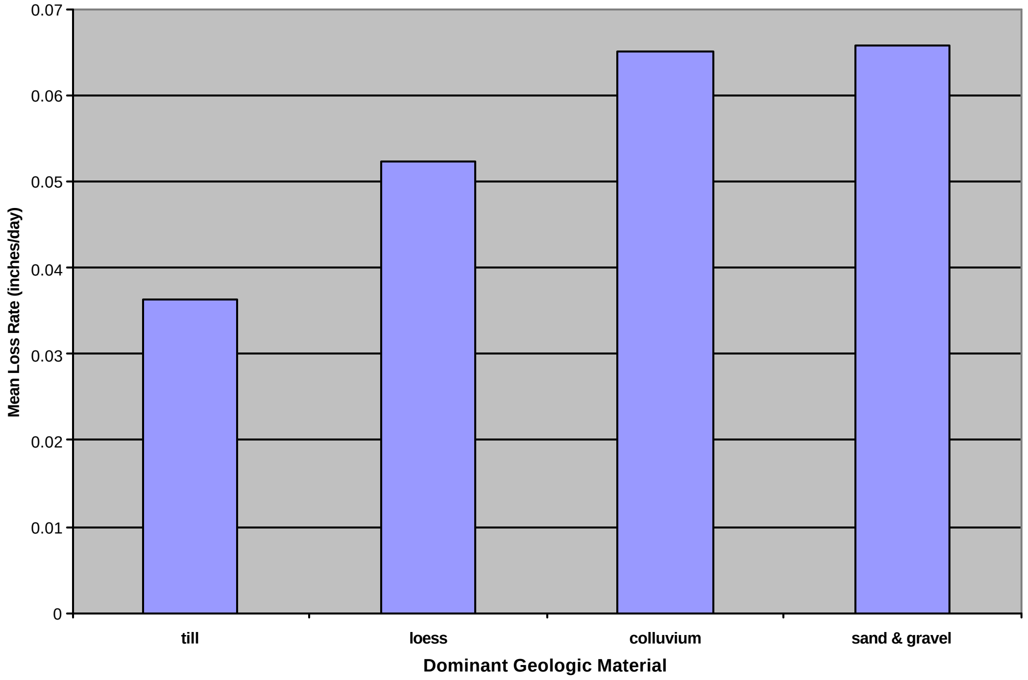

Figure 8. Mean seepage rates (at six-foot liquid depth) for structures grouped by dominant surficial geologic material (adjusted for age).

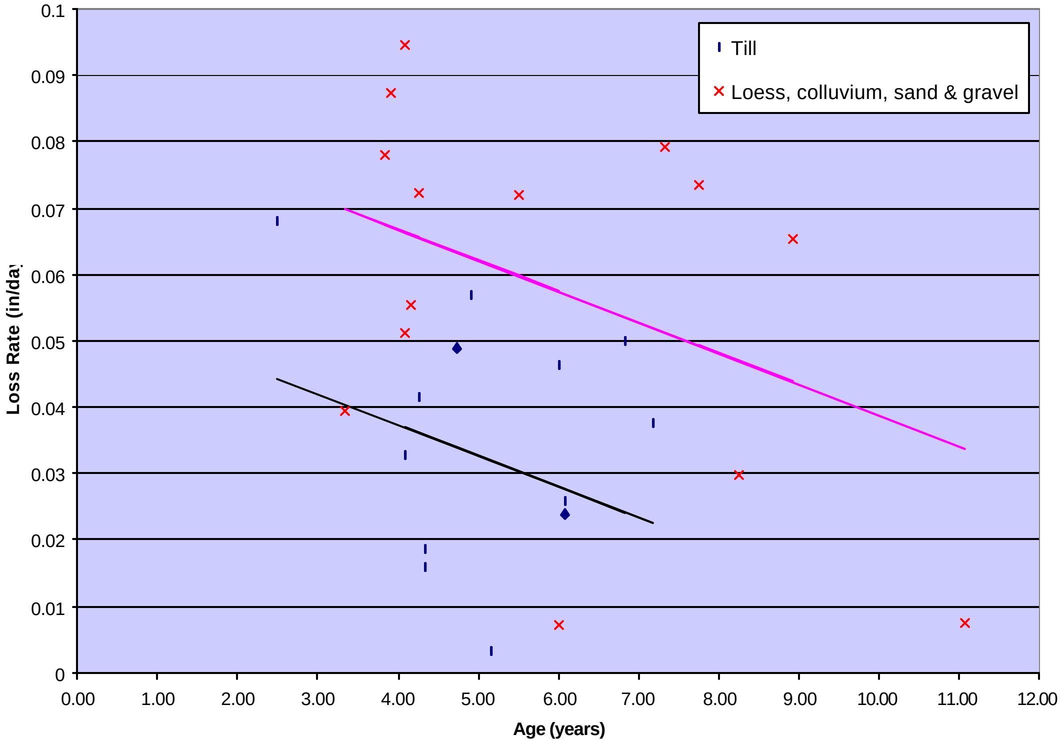

Figure 9. Mean liquid loss rates (at six-foot liquid depth) vs structure age for EWSS located in till and non-till settings.

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