HYDROGEOLOGIC SETTINGS OF EARTHEN WASTE STORAGE STRUCTURES ASSOCIATED WITH CONFINED ANIMAL FEEDING OPERATIONS IN IOWA

[2]W.W. Simpkins and [1]M.R. Burkart
[1]*USDA, Agricultural Research Service, 2150 Pammel Drive, Ames, IA 50011; Phone: (515)294-5809; Fax: (515) 294-8125.*
[2]*Department of Geological and Atmospheric Sciences, Iowa State University, Iowa State University, Ames, IA 50011; Phone: (515)294-7814; Fax: (515) 294-6049.*

ABSTRACT

Thirty-four permitted earthen waste storage structures (EWSS) were investigated to characterize their hydrogeologic setting using digital soils data, digital elevation data, geologic maps, and oblique aerial photographs. Nearly 18 percent of the sites were constructed above alluvial aquifers and on flood plains. More than half of the area within 3.2 km of most sites had soils with a vertical permeability = 25.4 mm/hr and well or moderately to well-drained soils. The prevalence of EWSS depths exceeding 3 m and areas with water table less than 1.6 m deep suggests that most sites are below the water table. Ephemeral or perennial streams were found within 152 m at one-third of the sites. Risks to water resources may be reduced by using siting criteria that incorporate geologic, hydrogeologic, and soils data. Controlling the timing of manure application and avoiding application on frequently flooded and permeable soils may reduce the risk of water-resource contamination. Application of well-established, scientifically defensible ground-water monitoring techniques should be used to locate the position of the water table during construction and throughout the life of the EWSS. Uniform stream setbacks may not be appropriate for all hydrogeologic settings. These considerations, used with appropriate performance standards, would reduce the potential for contamination of water resources.

Key words: hydrogeology, manure, soils, aquifers, streams

INTRODUCTION

Earthen waste storage structures (EWSS) are used extensively in Iowa to store wastewater and manure for treatment and/or land spreading. Swine production in confined or concentrated animal feeding operations (CAFOs) has increased their number in the 1990s at both state and national levels. This trend is shown in Iowa by an increase in swine production concomitant, with a decrease in the number of swine farms. The number of farms that raised swine decreased 80 percent from 90,000 in 1970 to 18,000 in 1996, while the number of animals per farm increased 330 percent (from 180 to 778 head) during that time (Seigley and Quade, 1998). Although there has been an increase in the use of EWSS for manure storage and public concern about the impact of these structures as the size of swine farms has increased, little is known about the hydrogeologic settings of EWSS. The purpose of this paper is to document the hydrogeologic settings of EWSS in Iowa, with reference to their potential impact on water resources in the state.

EARTHEN WASTE STORAGE STRUCTURES

EWSS consist of uncovered earthen impoundments constructed from native materials on site rather than concrete or imported materials. The process of construction involves excavation, sidewall construction with berms, and compaction of a liner made of native materials, all of which are important components to the long-term hydrologic integrity of the structure. Basins and lagoons are the common types of EWSS. Basins are the smaller of the two and provide short-term storage of undiluted manure waste. They are typically designed to hold 6 to 8 months of material prior to land spreading. The Iowa Department of Natural Resources (IDNR) requires waste from basins be removed and spread on the land at least twice a year. The manure in basins has a high nutrient content, typically 3.8 g/L as nitrogen (Simpkins et al., 2002). In contrast, manure is mixed with water in lagoons. The process increases the volume of waste stored and promotes anaerobic conditions that allow bacteria to reduce its nitrogen (N) content. Liquid is removed and applied to land at least once annually as required by the IDNR. At present, the rate of application is regulated by the N concentration of the manure. Because of the lower N concentration in lagoons (typically only 0.5 g/L), greater volumes of liquid waste may be applied per unit area than from a basin serving a similar number of animals. A typical field application rate for manure waste from a basin in Iowa is about 56,000 L/ha, while the application rate from a lagoon is about 40,000 L/ha for a yield goal of 81 kg N/ha (Simpkins et al., 2002).

Previous studies of the hydrogeologic settings of EWSS are few in number. The Geological Survey Bureau (GSB) of the IDNR investigated changes in groundwater quality adjacent to three EWSS located in north-central, east-central, and west-central Iowa and constructed in late Wisconsinan till, Pre-Illinoian till/ colluvium, and loess, respectively (Libra and Quade, 1997). Groundwater monitoring at the north-central and east-central EWSS has shown above-background concentrations of chloride (nearly 200 mg/L), total organic carbon (>100 mg/L), and fecal coliform bacteria to a distance of at least 46 m downgradient of the structure. Ammonium and phosphate concentrations are not greater than ambient concentrations found outside the structures, perhaps because these ions are retained on sediments surrounding the EWSS. Nitrate- and sulfate-ion concentrations outside the EWSS are below ambient concentrations and may have been reduced as a result of low reduction-oxidation (redox) potentials created by EWSS-derived organic carbon. None of the above-mentioned ions or bacteria has been observed in groundwater outside the western Iowa EWSS site in loess (Libra and Quade, 1997).

Legislative and Regulatory History

CAFO legislation and regulation in Iowa have evolved in response to the increase in EWSS. Permitting rules governing CAFOs are found in *Chapter 65* of the *Iowa Administrative Code*. In 1987, permits for construction of anaerobic lagoons were required, regardless of the number of animals on site. Legislation passed in 1995 (*House File 519*) revised *Chapter 65* and provides the basis for most of the present regulations. Senate File 2293, passed in 2002, provided further modification of the regulations. Since 1995, facilities that contain more than a total swine weight of 90,718 kg (approximately 1333 head at an average weight per animal of 68 kg) or 181,437 kg of cattle are required to submit plans for construction of a basin or lagoon. As of December 1997, there were 639 permitted CAFOs with EWSS in the state. By the end of 1999, construction of lagoons and basins had slowed due to a trend toward alternative storage strategies, such as concrete pits, formed (concrete) storage structures, and above-ground tanks. The number of permitted sites grew to only 661 by 1999 and, as of 2001, it stood at 729 sites. The IDNR estimates that 5000 additional CAFOs exist below the size thresholds necessary for construction permits. Location and hydrogeologic settings of these EWSS are generally unknown to the IDNR until an official manure management plan is filed in anticipation of land spreading activities.

Setbacks of EWSS from “navigable” streams have been used in Iowa regulations since 1995. “Navigable,” in Iowa, is defined as “…all streams that can support a vessel capable of carrying one or more persons during a total of a 6-month period in one out of every 10 years …” (Simpkins et al., 2002). In the 1999 revisions, “navigable” was changed to “major water source,” to which a setback distance of 152 m applies. Rivers, streams, and lakes that are not specifically listed in the regulations are now termed “water-courses,” with an associated setback distance of 61 m. Present rules require only that the top of the EWSS is 0.3 m above the elevation of the 100-yr flood plain. Other than a required separation distance of 152 m from a private well, construction of EWSS or any other treatment lagoons, on an aquifer that is being used for water supply has not been prohibited. Recent legislation (SF 2293) does address protection for designated aquifers and “high-quality water resources,” as defined in the *Iowa Administrative Code, Chapter 61*.

In Iowa, EWSS are permitted to leak at a maximum rate of 1/16 in/d (converted to 1.6 mm/d for this paper), although only those above the animal weight criterion are subject to review of site-construction plans. Iowa’s leakage-rate standard was derived from municipal lagoon technology. It is approximately equivalent to 3.6 times the leakage of a large septic system (MPCA, 1997). Until 1999, EWSS permits allowed leakage at that rate based on a uniform 1.8-m liquid depth. This construction standard will be referred to as the “old rules.” Subsequent revisions in 1999 required calculations based on the full design depth of the structure, which will be referred to as the “new rules.” Adherence to the leakage-rate standard is determined by laboratory estimates of hydraulic conductivity (K) in soil cores taken from the compacted liner at the time of construction. Laboratory estimates of K in fine-grained materials used for liner materials (predominantly till and loess) typically underestimate field values by one to two orders of magnitude (Bradbury and Muldoon, 1990; Simpkins and Bradbury, 1992), so leakage rates may be higher than the design standard. Permitted leakage rates can result in a substantial loss of fluid from EWSS. An “average” structure of 5815 m^2 will lose 3.4×10^6 L of fluid per year, while a “large” facility of 28,308 m^2 will lose 1.6×10^7 L of fluid per year. An average basin containing a manure waste concentration of 3.8 g/L N (mostly as NH_4-N) could lose 13,000 kg/yr of N by leakage.

New and old rules stipulate a separation distance of at least 1.2 m between the top of the EWSS liner and water table at the time of construction. A synthetic liner is necessary if the water table is less than 0.6 m below the top of the liner. Under the old rules, a water level in a single, open borehole was the only measurement necessary for determination of the water table. New rules require installation of a temporary well to be monitored for at least one week. Installation of a groundwater-monitoring network around EWSS, which may be required in certain hydrogeological situations in surrounding states, is not required in Iowa.

Purpose of Study

Although EWSS are intended to minimize problems associated with large quantities of manure, negative environmental impacts, resulting from spills, ruptures, and leaks, are associated with EWSS throughout the U.S. (Mallin, 2000). Groundwater may be contaminated directly by 1) leakage through the bottom or sides of EWSS (Huffman and Westerman, 1995; Parker et al., 1999); 2) leaching of nutrients and contaminants due to land spreading (Evans et al., 1984); and 3) surface water contaminated during flooding (Burkholder et al., 1997). Surface water may be contaminated directly by spills or leaks (Mallin et al., 1997) and indirectly through interception by drainage tiles. Surface water may subsequently lose water to alluvial aquifers, causing contamination of groundwater (Burkart et al., 1999).

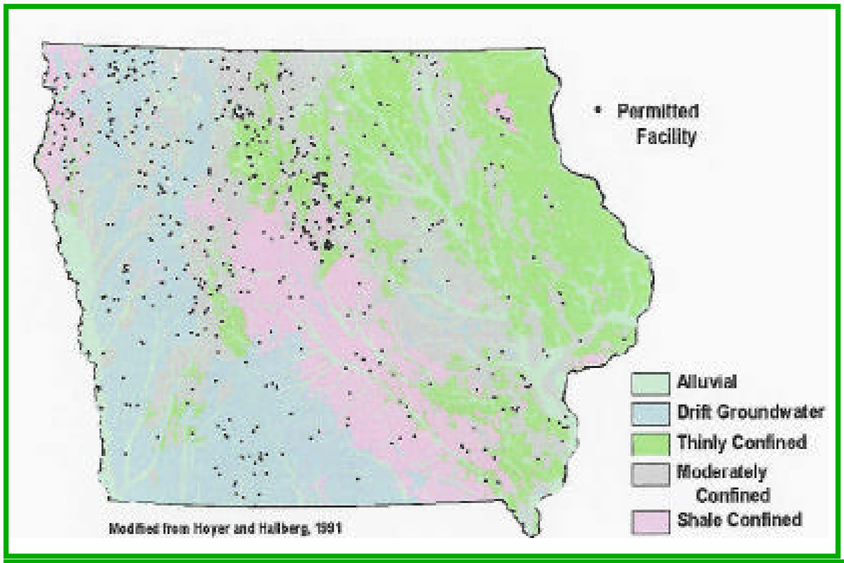

Figure 1a. Map showing the five aquifer vulnerability classes in Iowa and locations of all permitted earthen waste storage systems through 1997 (n=639).

Public concern about the potential of these structures to contaminate water resources has also increased. In response to this concern, the Iowa Legislature provided funds to Iowa State University (ISU) in 1997 "…to determine the extent to which structures [EWSS] contribute to point and nonpoint pollution in the state…" (*HF 708, Section 11, Animal Feeding Operations*). A team of 15 ISU researchers examined this problem and produced a report entitled "Earthen Waste Storage Structures in Iowa" (Iowa State University, 1999). This paper presents research on the hydrogeologic settings of EWSS, as given in the first chapter of that report (Simpkins et al., 1999).

PROCEDURES

Study Design

The study was limited to EWSS permitted between 1987 and 1994. This time period was chosen for two reasons. First, evidence in the literature suggests that freeze-thaw, desiccation during low-water levels, bioturbation, overland flow, and groundwater inflow cause deterioration of the liners and sidewalls of EWSS, which would significantly weaken their ability to contain wastes (Glanville et al., 1998). EWSS constructed prior to 1994 were presumed old enough to allow these processes to modify the structures, thus increasing the potential for transport of contaminants away from them. Second, permits issued before 1987 were not available in digital format and not readily accessible to the project. The final database consisted of 439 sites that were issued construction permits between 1987 and 1994.

To select a sample representing current conditions in Iowa, the entire IDNR database through 1997 also was examined to include more recent trends in construction. The IDNR issued 639 permits for EWSS by the end of 1997, including permits for 404 basins (63 percent) and 212 lagoons (33 percent) (Figure 1a, Table 1). The type of structure was not defined in 23 permits (4 percent), and many of the permitted EWSS were never actually built. Similar percentages of lagoons and basins were selected from the 1987 to 1994 database (n=439), based on data through 1997 (n=639). This ensured a sample that was representative of the entire EWSS population.

A questionnaire was sent to the 439 owner/operators of facilities to seek initial permission for on-site study. From 124 positive responses to this questionnaire, 40 EWSS were selected representing the important hydrogeologic settings in Iowa. A digital map of the Groundwater Vulnerability Regions of Iowa (Hoyer and Hallberg, 1991) was used to identify these settings and to classify the vulnerability of the aquifer at the EWSS. The eight-category classification of Hoyer and Hallberg (1991) was reduced to five categories, termed aquifer vulnerability classes (AVC). These included alluvial aquifers; drift aquifers (aquifers in

Table 1. Classification of permitted earthen waste storage systems (EWSS) through 1997, from the Iowa Department of Natural Resources database. Data sorted by aquifer vulnerability class (AVC).

			Type of Structure			Type of Animals		
Aquifer Vulnerability Class	Total Through 1997 (% of total)	1987-94 Study Sites (% of total)[1]	Lagoons	Basins	Other	Swine	Beef and Dairy	Poultry
Alluvial Aquifer	57 (9)	6 (18)	17	33	7	49	7	1
Drift Aquifer	159 (25)	7 (21)	41	114	4	147	7	5
Thin-drift Confinement	102 (16)	5 (15)	49	50	3	98	2	2
Moderate-drift Confinement	221 (35)	11 (32)	76	141	4	212	7	2
Shale Confinement	100 (16)	5 (15)	29	66	5	89	10	1
Total	639	34	212	404	23	595	33	11

[1]The original percentages of the sub-sample were nearly identical to those of the larger data set. Two sites were moved to the alluvial aquifer category when they were found to be mislocated geographically in the original digital database.

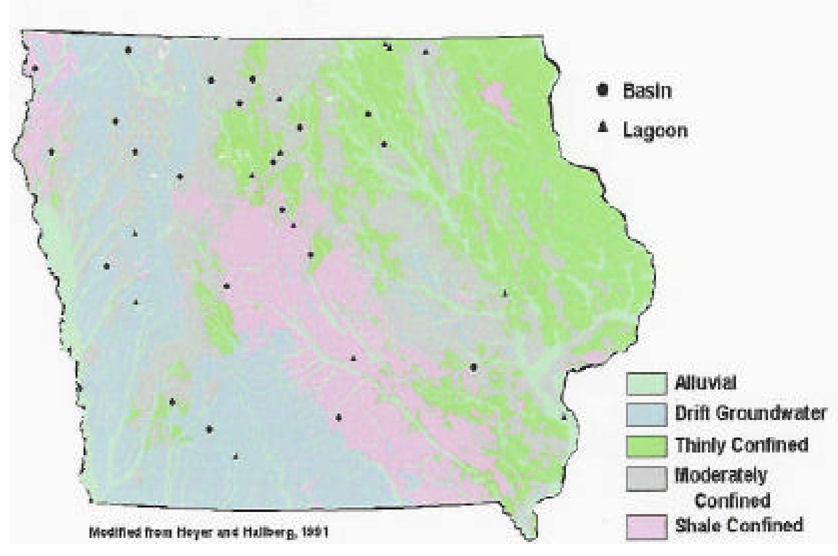

Figure 1a. Map showing the five aquifer vulnerability classes in Iowa and locations of earthen waste storage systems investigated in this study (n=34).

glacial sediments); and confined aquifers overlain by thin-drift thickness (< 30.5 m), moderate drift thickness (30.5 to 91.4 m), and any thickness of shale. In this paper, the latter three categories will be referred to simply as thin-drift confinement, moderate-drift confinement, and shale confinement. Based on positive responses to the questionnaire, a sub-sample of 56 EWSS was selected for further investigation. Owners/operators of the EWSS were then asked to sign a memorandum of understanding (MOU) that allowed ground and air access to the site. A final group of 40 EWSS, representing a wide geographic distribution and comprising about 9 percent of the 1987 to 1994 sample, was selected from positive responses to the MOU. The sub-sample approximately maintains the nearly 2:1 ratio of basins over lagoons and the percentages in each of the five AVCs in the larger database (Table 1), but it does not reflect the distribution of sites among surficial materials. Six sites were subsequently eliminated from the study because they were either unwilling to sign the MOU or initial field information showed they were not suitable for testing. The remaining 34 EWSS, consisting of 13 lagoons and 21 basins, were used for the study (Figure 1b). An additional lagoon near Iowa State University was added later for leakage calculations.

Sources of Data

Data from a digital soil database, county soil surveys, topographic and geologic maps, and aerial photographs were used to interpret the hydrogeologic setting of each EWSS and surrounding area. Digital soils data were obtained from the Map Unit Identification Records (MUIR) digital data base for Iowa, maintained by the Soil Survey Division of the Iowa Department of Agriculture and Land Stewardship and

ISU (www.statlab.iastate.edu/soils/muir/download.html, Jan 13, 1997). Soil mapping units were verified with the soil surveys for each county. Digital topographic data and scanned images of topographic maps from the U.S. Geological Survey also were used to locate EWSS, and to estimate distances to perennial and ephemeral streams. Geologic maps (Hallberg et al., 1991) and aerial photographs were used to classify EWSS by surficial-material categories of sand and gravel, loess, till, and colluvium.

Digital soil data were used primarily to assess the potential for leakage to the water table or for overland flow from fields on which manure may be applied. A circle of radius 3.2 km around each EWSS was defined as the manure-spreading area (MSA). For an average farrow-to-finish swine operation, it is not economically feasible to haul and apply manure more than a distance of 1.6 km (Brenneman, 1995); thus, 3.2 km is actually beyond the likely hauling distance. Soil variables selected for these analyses included equivalent vertical hydraulic conductivity, hydrologic group, flood frequency, and depth to the seasonally high water table. An average vertical hydraulic conductivity ($K_v$avg) was estimated for each soil using the equation (modified from Fetter, 2001; p. 106):

$$K_v avg = \frac{b}{\sum_{m=1}^{n} \frac{b_m}{K_{vm}}} \qquad (1)$$

Where K_{vm} = vertical hydraulic conductivity (K) of the *m*th layer (units of L/T)

b_m = thickness of the soil layer (units of L)

b = total thickness of the soil (units of L)

A value of 25.4 mm/hr, the approximate boundary between permeable sands and less-permeable silty sands (Freeze and Cherry, 1979), was used as a threshold between high and low values of K_v for manure application. Hydrologic group is a variable that incorporates soil properties influencing potential for overland flow and infiltration (Soil Survey Staff, 1996). Soils with large to moderate infiltration rates (groups A and B) have a high potential to transmit contaminants to groundwater. Soils with slow to very slow infiltration rates (groups C and D) have a greater potential to transport contaminants by overland flow. The depth to the seasonally high water table is a measure of the shallowest depth to saturation that may be expected during a typical year (Soil Survey Staff, 1996).

A one-year recurrence interval was used for flood-frequency data in this analysis, and the data were subdivided into frequent and occasional floods. Frequent floods have a 50-percent chance or more of occurring in any one year, while occasional floods have a 5- to 50-percent chance in any year (Soil Survey Staff, 1996). Manure applied to soils with the high probability of flooding will most likely contaminate nearby streams. Flooding could also erode and breach the berms of EWSS.

Topographic maps were used to identify hydrologic and cultural features, and to measure the approximate distance to features that may influence or be influenced by the operation of EWSS or the application of manure in the site area. Examples of such features included surface-water bodies, communities, institutions, and recreational facilities. Both perennial and ephemeral streams were identified in the analysis. A perennial stream flows continuously throughout the year, whereas an ephemeral stream flows only in response to precipitation (Bates and Jackson, 1980). The maps also were used to describe slopes and the geomorphology at each EWSS. Geomorphic features were used in combination with geologic and soil maps to interpret the surficial geologic material and the most likely geologic material at the base of the excavated EWSS. Oblique aerial photographs were taken from a fixed-wing aircraft at an altitude of approximately 300 m, to facilitate interpretation of the geomorphic and hydrologic features and to confirm the position of the EWSS.

In addition to data specific to this study, data from Glanville et al. (1999) were used to compare leakage rates among surficial materials and AVCs. Their estimates were made using a mass-balance technique, in which water-level decline and meteorological conditions (e.g., temperature, humidity, wind speed) were observed on multiple occasions during a 3- to 10- day period after pumping into and out of the EWSS ceased. The data at each site demonstrated a large variance. Estimates were made at only 27 of the 34 structures, because the data either were not interpretable or some EWSS were not amenable to the necessary measurements. One additional site in central Iowa that was maintained by ISU was added to the database, bringing the final number to 28. Because 80 percent of the sites were filled only to within 1 m of their design depth, Darcy's Law was used to convert leakage values measured from existing liquid levels to both the 1.8-m liquid depth (the old rules) and full-design depth (the new rules). Evaporation losses were not differentiated from actual EWSS leakage, because evaporation was difficult to quantify and assumed to be insignificant. Because the raw leakage and evaporation data were not available to our study, the reader is referred to Glanville et al. (1999) for a complete discussion.

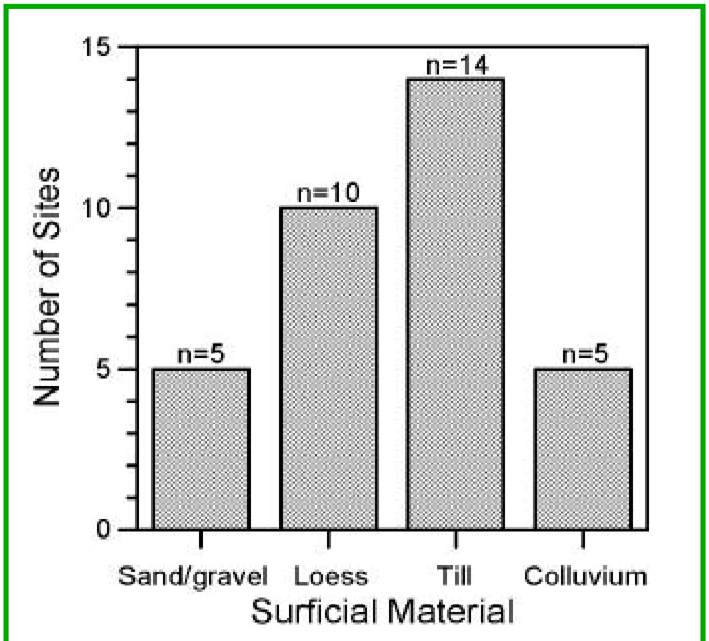

Figure 2a. Bar graph showing distribution of earthen waste storage systems investigated in this study (n=34) classified by surficial material.

Statistical Analysis

Nonparametric statistical techniques (Conover, 1980) were used to compare leakage rates among surficial materials and AVCs, and to distinguish significant differences between leakage rates under the old and new rules. The "standard boxplot" (Helsel and Hirsch, 1992;) was used to graphically show the median, upper, and lower quartiles; whiskers; and outliers for each sample category. Median leakage rates from surficial geologic units and AVCs were compared using the nonparametric Kruskal-Wallis test (Kruskal and Wallis, 1952) and two-tailed Mann-Whitney test (Mann and Whitney, 1947). Data were categorized by surficial material, and AVC and the medians were compared to the 1.6 mm/d construction standard under the old and new rules. The Wilcoxon Signed-Rank procedure (Wilcoxon, 1945; Helsel and Hirsch, 1992) was used to test significant differences of each group's median from the construction standard.

RESULTS AND DISCUSSION

Hydrogeologic Settings of EWSS

Analysis of the data indicated that 14 EWSS (41 percent) are constructed in till, either of late Wisconsinan or Pre-Illinoian age (Figure 2a). Most occur in late Wisconsinan till associated with the Des Moines Lobe in north central Iowa. Till units there are part of the Dows Formation, which consists of a basal till unit, the Alden Member, and a supraglacial unit, the Morgan Member. The former is generally compact, homogeneous in texture with depth, and extensively fractured (Eidem et al., 1999). The latter is

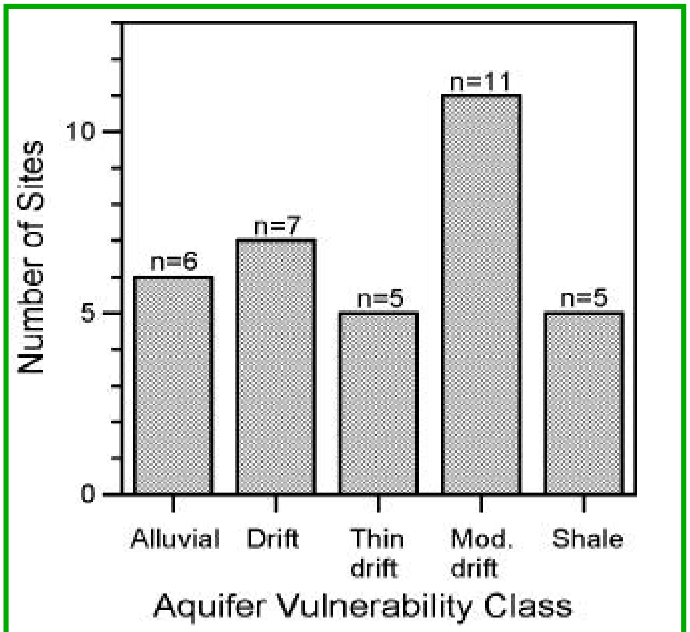

Figure 2b. Bar graph showing distribution of earthen waste storage systems investigated in this study (n=34) classified by aquifer vulnerability class.

more heterogeneous, less consolidated, but is also fractured. The Morgan Member also contains sand in linked, subglacial channels, which, when exposed on the walls of newly constructed EWSS, are known to cause instability in the compacted liner (Simpkins et al., 2002). Thicknesses of weathered till range from 3 m in the Des Moines Lobe, up to 10 m in older Pre-Illinoian deposits in the rest of the state. The sidewalls of EWSS may be in contact with the weathered zone of either unit. Studies of chemical transport in the weathered zone show velocities of nearly 11 m/day due to fracture flow (Helmke et al., 1999). Based on the depth of the structures and discussions with DNR personnel and site engineers, the base of EWSS in the Des Moines Lobe is usually excavated into the denser, unweathered till. Fracture density in unweathered till is less, and overall chemical transport velocities may be less than 0.1 m/day (Helmke et al., 1999). The base of EWSS may lie within the weathered zone of Pre-Illinoian till in areas outside the Des Moines Lobe.

The majority (21 of 34 EWSS; 62 percent) of EWSS surveyed in this study overlie confined aquifers (Figure 2b). Six of 34 EWSS (18 percent) directly overlie an alluvial aquifer. This aquifer type is generally recognized as the most vulnerable and most productive in Iowa. It is the most widely used aquifer for domestic and municipal water supplies (IGWA, 1990; Burkart and Kolpin, 1993). The aquifer is particularly vulnerable because it lies close to land surface and is recharged predominantly by vertical infiltration through the unsaturated zone. In addition, the base of the excavation may lie below the water table and top of the aquifer, thus increasing the potential for contamination of a domestic or municipal water

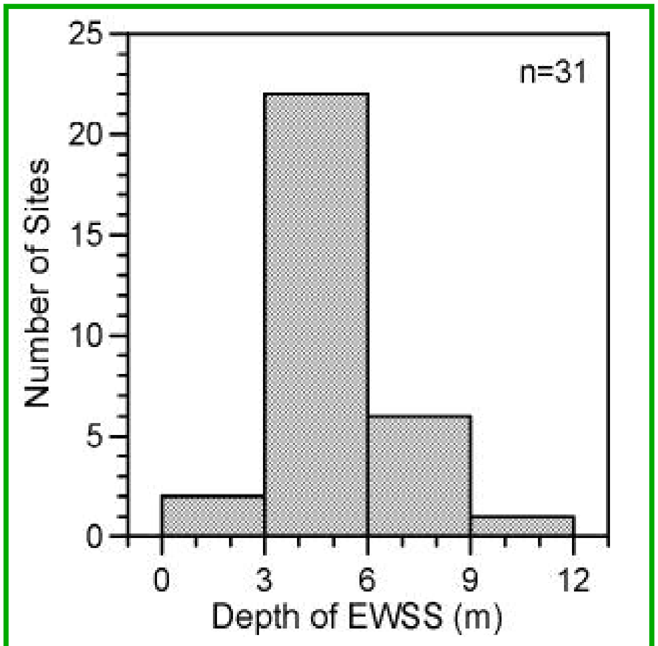

Figure 3. Histogram showing distribution of depth among earthen waste storage structures (n=31). Depth includes berm height.

supply drawing from that aquifer. One EWSS in this study was located in an alluvial aquifer on a floodplain that was adjacent to active sand and gravel pits.

Comparison of the total depths of EWSS and seasonally high water tables suggest that most EWSS excavations in this study were below or are at least in contact with the water table at the time of their construction. Rules require a minimum depth of 2.4 m and a 0.6 m freeboard (distance between the maximum water level and the top of the berm) (Zhang et al., 1995), which means that the structure will be excavated with the depth plus berm height greater than 3 m. Twenty-nine of the 31 EWSS (94 percent) with depth data were deeper than 3 m. Most of the EWSS (22 of 31; 71 percent) were between 3 and 6 m deep (Figure 3). Further examination showed that 22 of 34 (65 percent) were within an MSA where 50 percent or more of the area had water- table depths less than 1.6 m (Figure 4). Field evidence indicated that the water table was within 2.4 m of the land surface at 20 of the 28 EWSS (71 percent) in the larger study (Baker et al., 1999). The 1.2-m separation between the top of the liner and water table could not have been met in these cases. In addition to decreasing the effective storage capacity of the EWSS, construction below the water table has, in the short term, caused groundwater flow into the structure prior to filling. Anecdotal reports from the IDNR indicate that inflow has resulted in slope failure in the sidewalls and affected the integrity of the compacted liner. In the long term, construction of EWSS above or below the water table will likely create a mound and establish a hydraulic gradient outward from the structure. Assuming a

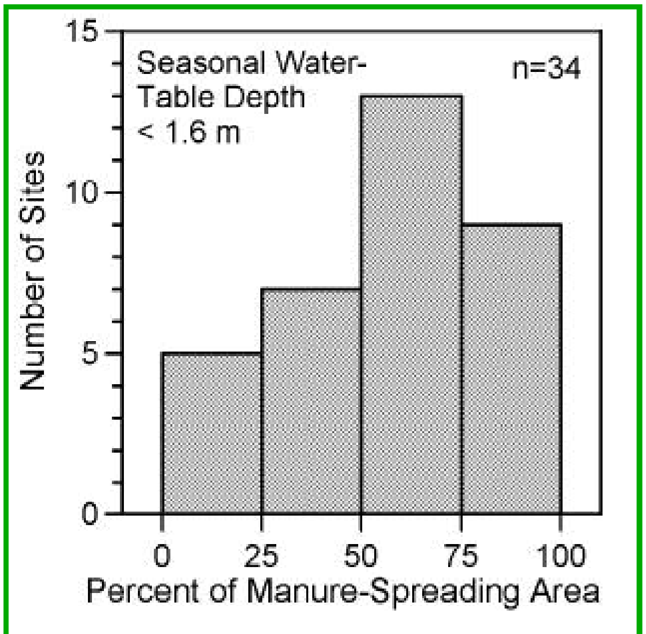

Figure 4. Histogram showing number of earthen waste storage systems and the percent of their surrounding manure-spreading area in which seasonal water table depth is less than 1.6 m (n-34).

specific yield value in the material of 0.2, leakage from an average EWSS within the study period may have raised the water table locally by 3 m.

Land Spreading

Although construction of EWSS on permeable soil creates an obvious risk to groundwater, leaching and overland flow on land designated for manure application are also important. Drainage characteristics of the soil are one factor that should control how much manure may be applied without negatively impacting groundwater. Specifically, more land is necessary to safely utilize manure in areas of well-drained soils than in areas of poorly drained soils. Twenty-five of 34 EWSS (74 percent) lie within MSAs more than 90 percent dominated by soils with vertical permeability exceeding 25.4 mm/hr. MSAs with 50 percent or more soils in hydrologic groups A and B (well-drained and moderately to well-drained soils) also occur at 25 of the 34 EWSS (74 percent). Presumably, vertical infiltration would dominate at these EWSS. MSAs where soils are mapped within hydrologic groups C and D (moderately poor to poorly drained) predominated at only 7 EWSS (21 percent). In addition to overland flow in poorly drained areas, drainage tile intakes may intercept contaminants, particularly if manure application immediately precedes rainfall or snowmelt events, and transport them to surface water.

Distance to Surface Water

EWSS in this study were generally greater than 61 m from a river, stream, or lake, even though there was no enforced setback distance at the time of construction. Many, but not all, reaches of perennial streams identified in the present study were listed as navigable in the *Iowa Administrative Code*; however, none of the ephemeral streams met this definition. Eighteen ephemeral and 19 perennial streams were identified at the 34 EWSS. Both types of streams occurred near three EWSS and were counted in both categories. Four of 19 EWSS (21 percent) near perennial streams were within 152 m of them, which if interpreted as a "major water source," would violate the new rules. Two of 18 EWSS (11 percent) near ephemeral streams were within 61 m of them, which, if interpreted as "watercourses," would also violate the new rules. Use of the "navigable" definition has allowed some creative uses of existing drainage networks to facilitate construction of EWSS. One such structure was built by damming an ephemeral stream channel that leads downward very steeply to a major navigable river.

Risk of Flooding

Flooding poses a substantial risk for surface-water contamination when lands used for spreading are inundated. Loss of structural stability and subsequent erosion and breaching of berms are also concerns related to flooding (Mallin, 2000). Although the majority of EWSS in this study (24 of 34; 71 percent) are surrounded by MSAs where less than 10 percent of the area may have been frequently flooded, ten of 34 (29 percent) had MSA where greater than 10 percent of the land is frequently flooded. Many of these were located on alluvial aquifers, which pose particular risks to groundwater quality due to recharge of floodwater to groundwater and high water tables associated with rising stream stage.

Hydrogeologic Settings and Leakage Rates

Hydrogeologic setting should exert some influence on EWSS leakage rates and affect the potential impact of leakage on nearby water resources. Consequently, knowledge of hydrogeologic settings could be used to suggest areas in the state that should be avoided for future EWSS. Leakage data obtained from 28 EWSS (Glanville et al., 1999) were grouped according to their AVCs (five classes) and the dominant surficial material (three classes). In the latter, two EWSS classified within colluvium were judged too small for an analysis as a class. They were included within the till class because they contained mostly fine-grained sediment. Differences in leakage rates among surficial materials and AVCs were investigated, as well as whether leakage rates were significantly greater or less than the construction standard of 1.6 mm/d.

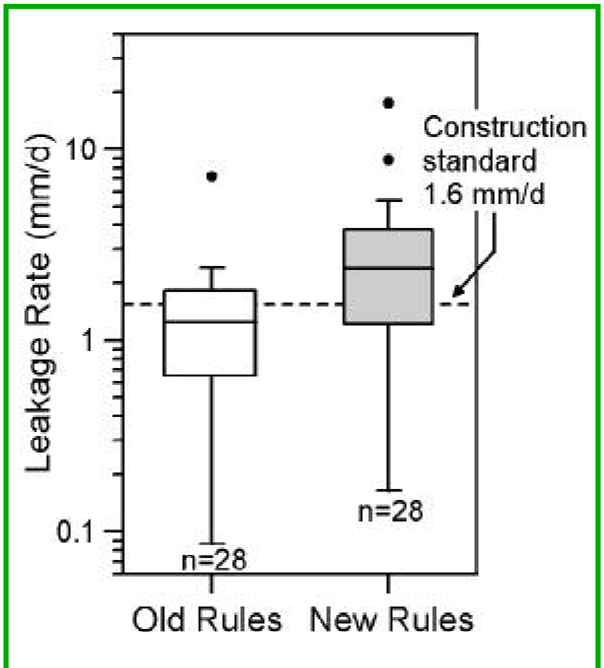

Figure 5. Boxplots showing leakage rates for all earthen waste storage systems under both old and new rules (n=28). Construction standard of 1.6 mm/d is shown by the dashed line.

Boxplots indicate that combined leakage rates computed for the old and new rules are significantly different ($\alpha = 0.05$ level; Figure 5), indicating that the assumptions (i.e., K, hydraulic gradient) made in calculating leakage rates strongly influence the reported rate. Some differences in leakage rates exist among the 28 EWSS in different surficial materials (Figure 6) and AVCs (Figure 7). However, Kruskal-Wallis (Kruskal and Wallis, 1952) and Mann-Whitney (Mann and Whitney, 1947) tests both indicate that none of the differences in the medians are significantly different at the $\alpha = 0.05$ level. This suggests that the surficial materials and the AVC are less important in predicting differences among the leakage rates than are initial construction practices and/or subsequent K changes due to settling of solids. However, because of the large confidence intervals associated with the means in the original data, the lack of significant differences among classes may also reflect random error introduced during data collection. Results of the Wilcoxon Signed-Rank test (Wilcoxon, 1945; Helsel and Hirsch, 1992) indicate that the median leakage rate from all 28 EWSS is not significantly different ($\alpha = 0.05$ level) from the 1.6 mm/d standard under the old rules. However, the median leakage rate is significantly different from the standard under the new rules (Figure 5). With the exception of EWSS in loess (under the new rules), median leakage rates for individual surficial materials are not significantly different ($\alpha = 0.05$ level) from the standard under the old or new rules (Figure 6). EWSS in well-drained loess may leak more than in other materials due to the presence of macropores and fractures. Median

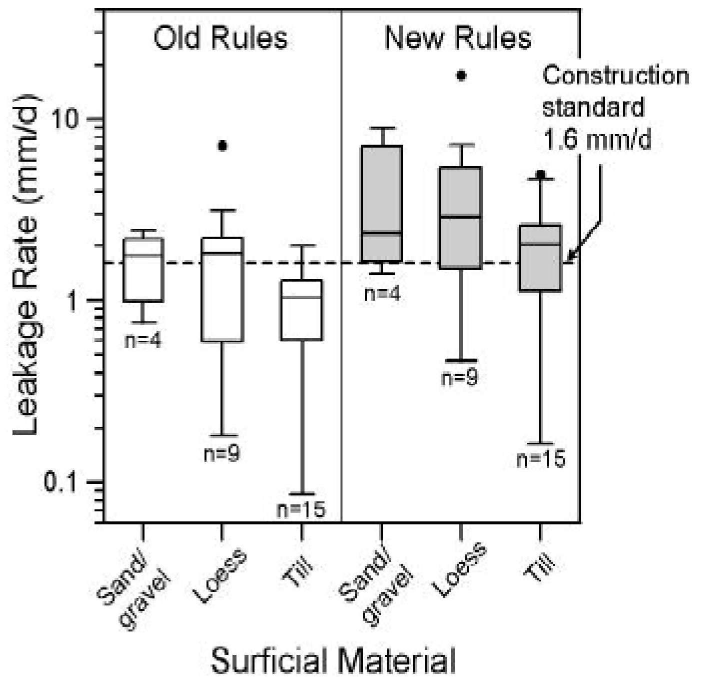

Figure 6. Boxplots showing leakage rates classified by the surficial material under both old and new rules (n=28). Construction standard of 1.6 mm/d is shown by the dashed line.

leakage rates for individual AVCs are not significantly different ($\alpha = 0.05$ level) than the leakage standard in the old rules (Figure 7). For the new rules, only EWSS in the moderate-drift confinement category show significantly greater leakage ($\alpha = 0.05$ level) than the standard, an interesting result given the thickness of drift and its low K value. Statistical differences from the standard in the other classes (such as the thin-drift class) may be affected by small sample sizes, which tend to emphasize values that might be outliers within larger samples. The drift aquifer category shows a wide interquartile range of leakage rates, perhaps indicating the presence or absence of interconnected sand bodies.

In summary, results from the statistical analyses suggest that neither the type of surficial materials nor the underlying aquifer probably affected the magnitude of leakage rates at EWSS in this study. However, the median leakage rate from our sample was significantly greater than the new rules allow. At least 50 percent of EWSS (14 of 28) were not in compliance with the newer construction standard—a larger value than the 10 of 28 (36 percent) suggested by Glanville et al. (1999).

CONCLUSIONS

This study investigated the hydrogeologic settings of 34 EWSS permitted between 1987 and 1994 in Iowa. Results suggest that hydrogeologic setting was not a major criterion in siting EWSS during that period. In particular, nearly 18 percent of EWSS (6 of 34) in the study were sited on alluvial aquifers,

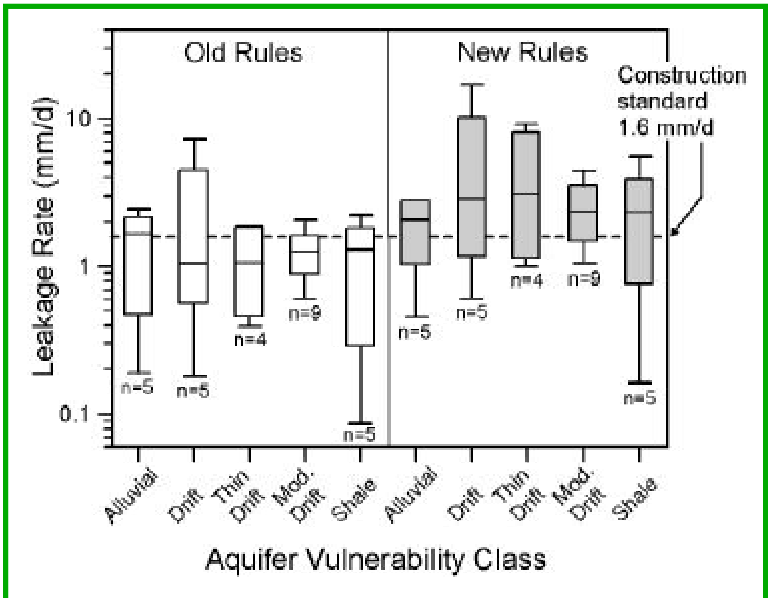

Figure 7. Boxplots showing leakage rates classified by the aquifer vulnerability class under both old and new rules (n=28). Construction standard of 1.6 mm/d is shown by the dashed line.

considered to be the most vulnerable type of aquifer in Iowa, and where the entry of contaminants could potentially impact municipal and domestic water supplies. In addition, most EWSS in alluvial aquifers lie in the flood plain, where there is a continual risk of flooding and entry of contaminants into surface water from manure application and berm failure. Elevated water tables associated with rising stream stage may compromise EWSS liner integrity and increase potential for failure long before a 100-year flood occurs.

Most of the manure spreading areas (MSA; areas within 3.2-km radius of the EWSS) contain permeable soils that may increase the potential for groundwater contamination. Drainage tiles can transport contaminants to streams in poorly drained land. Controlling the timing of manure application and avoiding manure application on frequently flooded soils, such as those on flood plains, may reduce the potential for contamination of groundwater and surface water.

The predominance of EWSS with depths equal to or exceeding 1.6 m suggests that most now lie below the water table and have impacted the surrounding groundwater resource. Established groundwater monitoring techniques should be used to locate the position of the water table during EWSS construction. Although rules now require installation of a temporary monitoring well, continued monitoring to check the status of hydraulic separation between the EWSS liner and the water table would ensure that the separation is maintained during the life of the structure. Based on our previous experience in surficial materials in Iowa (e.g., Eidem et al., 1999), it is likely that EWSS built under deeper water table conditions in the fall or winter may have saturated liners by springtime. Analysis of longer term water table fluctuations in various surficial materials statewide may be helpful in estimating probable water table depths in areas of proposed EWSS.

The effect of the hydrogeologic setting on leakage rates was examined by classifying the EWSS into five aquifer vulnerability classes (AVCs) and three surficial material classes. Leakage rates did not differ significantly among surficial materials or AVCs, suggesting that the hydrogeologic setting alone does not control leakage rates. Median leakage rates were significantly greater than the 1.6 mm/d leakage standard under the new rules. By inference from our sample of leakage rates at 28 sites, at least 50 percent of 439 EWSS built between 1987 and 1994 could leak at rates greater than allowed by Iowa regulations. It is likely that 50 percent non-compliance with the construction standard is a conservative estimate because of the bias introduced by the site-selection process in this study.

Finally, the impact of EWSS on water resources may be lessened by adopting regulations that require a better understanding of the hydrogeologic setting. Although used to some extent today, GIS databases could be more widely used during the EWSS permitting process and for manure-management plans. Unfortunately, permitted EWSS now comprise a minority in the state. Approximately 5,000 CAFOs fall under the legal size necessary for obtaining a construction or manure-spreading permit, and there is no effective guidance or regulation of their siting and construction. The hydrogeologic settings of these CAFOs are generally unknown to IDNR, even though activities at these sites also pose a risk to water resources (Simpkins et al., 2002).

ACKNOWLEDGMENTS

Funding for this research was provided by the state of Iowa *(HF 708, Section 11, Animal Feeding Operations*) and the opinions, findings, and conclusions expressed are those of the authors and not necessarily those of the state of Iowa.

REFERENCES

Agena, U., 1998. Overview and Status of State Programs Regulating Animal Feeding Operations, In: Proceedings for Watershed Partnerships: Protecting our Water Resources. Jan 20-21, 1998, Ames, Iowa, pp. 47-51.

Baker, J.L., T.D. Glanville, S.W. Melvin, and L.E. Shiers, 1999. Soil Sampling and Analysis Around Earthen Waste Storage Structures in Iowa, In: Earthen Waste Storage Structures in Iowa: A Study for the Iowa Legislature, August 1999, pp. 64-114.

Bates, R.L., and J.A. Jackson, 1980. Glossary of Geology, American Geologic Institute, Falls Church, Virginia, 749 pp.

Bradbury, K.R., and M.A. Muldoon, 1990. Hydraulic Conductivity Determinations in Unlithified Glacial and Fluvial Materials, In: D.M. Nielsen and A.I. Johnson (Ed.). Ground Water and Vadose Zone Monitoring, ASTM STP 1053, American Soc. for Testing and Materials, Philadelphia, pp. 128-151.

Brenneman, G., 1995. You Can't Afford Not to Haul Manure. Iowa State University, University Extension Livestock Industry Facilities and Environment Publication PM-1609, 2 pp.

Burkart, M.R., and D.W. Kolpin, 1993. Hydrologic and Land-Use Factors Associated with Herbicide and Nitrate in Near-Surface Aquifers, J. Environ. Qual., 22, pp. 646-656.

Burkart, M.R., W.W. Simpkins, M.F. Helmke, and P.J. Squillace, 1999. Infiltration of Herbicides to an Alluvial Aquifer Through Tributary Stream Leakage, J. Environ. Qual., 28, pp. 69-74.

Burkholder, J.M., M.A. Mallin, H.B. Glasgow, Jr., L.M. Larsen, M.R. McIver, G.C. Shank, N. Deamer-Melia, D.S. Briley, J. Springer, B.W. Touchette, and E.K. Hannon, 1997. Impacts to a Coastal River and Estuary from Rupture of a Swine Waste-Holding Lagoon. J. Environ. Qual., 26, pp. 1451-1466.

Conover, W.J., 1980. Practical Nonparametric Statistics, New York, John Wiley and Son, 2nd ed., 493 pp.

Eidem, J.M., W.W. Simpkins, and M.R. Burkart, 1999. Geology, Groundwater Flow, And Water Quality In The Walnut Creek Watershed. J. Environ. Qual., 28, pp. 60-68.

Evans, R.O., P.W. Westerman, and M.R. Overcash, 1984. Subsurface Drainage Water Quality from Land Application of Swine Lagoon Effluent. Transactions of ASAE, 27, pp. 473-480.

Fetter, C.W., 2001. Applied Hydrogeology, Prentice-Hall, Englewood Cliffs, 598 pp.

Freeze, R.A., and J.A. Cherry, 1979. Groundwater, Prentice-Hall, Englewood Cliffs, 604 pp.

Glanville, T.D., J.L. Baker, S.W. Melvin, T.L. Richard, W.W. Simpkins, M.R. Burkart, and J.L. Hatfield, 1998. Impacts of Seepage from Earthen Waste Storage Structures, In: Animal Production Systems and the Environment: an International Conference on Odor, Water Quality, Nutrient Management, and Socioeconomic Issues, Proceedings Volume I: Oral Presentations, pp. 457-462.

Glanville, T.D., J.L. Baker, S.W. Melvin, and M.M. Agua, 1999. Measurement of Seepage from Earthen Waste Storage Structures in Iowa, In: Earthen Waste Storage Structures in Iowa: A Study for the Iowa Legislature, August 1999, pp. 38-63.

Hallberg, G.R., J.A. Lineback, D.M. Mickelson, J.C. Knox, J.E. Goebel, H.C. Hobbs, J.W. Whitfield, R.A. Ward, J.D. Boellstorf, J.B. Swinehard, and V.H. Dreeszen, 1991. Quaternary Geologic Map of the Des Moines 4º x 6º Quadrangle, United States. U.S. Geological Survey, Miscellaneous Investigations Series Map I-1420 (NK-15).

Helmke, M.F., W.W. Simpkins, and R. Horton, 1999. Use of Multiple Tracers and Measured Effective Diffusion Coefficients to Constrain Solute Transport Models in Fractured Till, Geol. Soc. Am. Absts. with Progs. 31, 7, A-450.

Helsel, D.R., and R.M. Hirsch, 1992. Statistical Methods in Water Resources, Elsevier, Amsterdam, Studies in Environmental Science 49, 522 pp.

Hoyer, B.E., and G.R. Hallberg, 1991. Groundwater Vulnerability Regions Of Iowa. Geological Survey Bureau Special Map Series II.

Huffman, R.L., and P.W. Westerman, 1995. Estimated Seepage Losses from Established Swine Waste Lagoons in the Lower Coastal Plain of North Carolina. Trans. of the ASAE, 38, pp. 449-453.

Iowa Groundwater Association (IGWA), 1990. Iowa's Principal Aquifers: A Review of Iowa Geology and Hydrogeologic Units, Iowa Groundwater Association, 26 pp.

Iowa State University, 1999. Earthen Waste Storage Structures in Iowa: A Study for the Iowa Legislature, EDC-186, 114 pp.

Kruskal, W.H., and W.A. Wallis, 1952. Use of Ranks in One-Criterion Variance Analysis, Journal of American Statistical Association, 47, pp. 583-621.

Libra, R.D., and D.J. Quade, 1997. Update: Groundwater Monitoring at Earthen Manure Storage Structures, Iowa Geological Survey Bureau, unpublished report, 16 pp.

Mallin, M.A., J.M. Burkholder, M.R. McIver, G.C. Shank, H.B. Glasgow, Jr., B.W. Touchette, and J. Springer, 1997. Comparative Effects of Poultry and Swine Waste Lagoons on the Quality of Receiving Streamwaters. J. of Environ. Qual., 26, pp. 1622-1631.

Mallin, M.A., 2000. Impacts of Industrial Animal Production on Rivers and Estuaries. American Scientist, 88, pp. 26-37.

Mann, H.B., and D.R. Whitney, 1947. On a Test of Whether One or Two Random Variables Is Stochastically Larger than the Other, Annals of Mathematical Statistics, 18, pp. 52-54.

Minnesota Pollution Control Agency (MPCA), 1997. Technical Guidance for Groundwater Monitoring at New Feedlots in Minnesota, July 1997, 7 pp.

Parker, D. B., D.D. Schulte, and D.E. Eisenhauer, 1999. Seepage from Earthen Animal Waste Ponds and Lagoons – An Overview of Research Results and State Regulations. Transactions of ASAE, 42, pp. 485-493.

Seigley, L., and D.J. Quade, 1998. An Introduction to Hogs in Iowa, In: Fossil Shells, Glacial Swells, Piggy Smells and Drainage Wells: The Geology of the Mason City, Iowa, Area, Geological Society of Iowa Guidebook 65, pp. 47-50.

Simpkins, W.W., and K.R. Bradbury, 1992. Groundwater Flow, Velocity, and Age in a Thick, Fine-Grained Till Unit in Southeastern Wisconsin, J. of Hydrol., 132, pp. 282-319.

Simpkins, W.W., M.R. Burkart, M.F. Helmke, T.N. Twedt, D.E James, R.J. Jaquis, and K.J. Cole, 1999. Hydrogeologic Settings of Selected Earthen Waste Storage Structures Associated with Confined Animal Feeding Operations in Iowa, In: Earthen Waste Storage Structures in Iowa: A Study for the Iowa Legislature, August 1999, pp. 1-25.

Simpkins, W.W., M.R. Burkart, M.F. Helmke, T.N. Twedt, D.E James, R.J. Jaquis, and K.J. Cole, 2002. Potential Impact of Earthen Waste Storage Structures on Water Resources in Iowa, J. American Water Resources Association, 38, pp. 759-771.

Soil Survey Staff, 1996. National Soil Survey Handbook, Washington, D.C., Natural Resources Conservation Service, Title 430-VI.

Wilcoxon, F., 1945. Individual Comparisons by Ranking Methods, Biometrics 1, pp. 80-83.

Zhang, R., J. Lorimor, and S.W. Melvin, 1995. Design and Management of Anaerobic Lagoons in Iowa for Animal Manure Storage and Treatment, Iowa State University, University Extension Publication Pm-1590, 10 pp.