Effects of Liquid Manure Storage Systems on Ground Water Quality – Summary Report

April, 2001

Published by
Minnesota Pollution Control Agency

Prepared by
Ground Water Monitoring and Assessment Program

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Glossary

Animal Units: A unit of measure used to compare differences in the production of animal manure that employs as a standard the amount of manure produced on a regular basis by a slaughter steer or heifer. One slaughter steer = 1 animal unit; one swine = 0.3 animal unit; one turkey = 0.018 animal unit.

Concrete-lined manure storage systems: Poured concrete walls and floors, typically located directly below the barns. Standards for concrete liners have recently become more stringent.

Earthen-lined manure storage system: Compacted cohesive soils, typically constructed with a minimum of two feet of compacted cohesive soil. Standards for earthen liners have recently become more stringent.

Excess Chemical Concentration: Ground water loading of a chemical from a manure storage area. Excess chemical concentration represents the difference in chemical concentrations between wells located down-gradient and up-gradient of the manure storage area. For example, assume Well 1 is up-gradient and has a total nitrogen concentration of 10 mg/L. Wells 2, 3, and 4 are located 50, 100, and 300 feet down-gradient of the manure storage area and have concentrations of 50 mg/L, 10 mg/L, and 5 mg/L, respectively. Excess nitrogen in Wells 2, 3, and 4 is 40 mg/L (50 minus 10), 0 mg/L (10 minus 10), and –5 mg/L (5 minus 10), respectively.

Geosynthetic-lined manure storage system: An earthen basin that is lined with a synthetic material and a layer of bentonite.

Indicator: A measurement used to detect potential ground water impacts from manure storage systems. Indicators include nitrogen (ammonia, nitrate, Kjeldahl nitrogen), organic carbon, Eh, specific conductance, chloride, potassium, sodium, phosphorus, and dissolved oxygen.

Open Feedlot: An outdoor lot where animals are raised, fed, and held in a fenced area with native soils devoid of vegetation.

Unlined manure storage system: Manure storage basins constructed by excavating soils, with no record of any sort of a liner having been constructed.

Acknowledgements

We would like to thank individuals who spent considerable time reviewing this document, including Dr. Chuck Clanton (University of Minnesota), Russ Derickson (Minnesota Department of Agriculture), Dr. Robert Libra (Iowa Geological Survey), Jim Ruhl (United States Geological Survey), Dr. Sara Smith (Iowa Department of Natural Resources), Jim Sullivan (MPCA), Paul Trapp (MPCA), and Dave Wall (MPCA). Much of the data and many of the monitoring networks utilized for this study are the result of hard work by individuals too numerous to mention. We thank individuals responsible for constructing and maintaining the lysimeters in Morrison, Nicollet, and Dodge County, and individuals responsible for establishing well and tile monitoring networks at the feedlots included in this study. Numerous people helped us identify and gain access to sites for conducting temporary well studies, including Dave Wall (MPCA), Dave K. Johnson (MPCA), staff from Stearns County Soil and Water Conservation District, and staff from Stearns County Natural Resource Conservation Service. Finally, we thank all the individual feedlot owners who worked with us to collect this important information.

Foreword

This paper provides a summary of investigations of ground water quality impacts from liquid manure storage systems. The report includes information from several different studies in Minnesota, as well as a literature review. Most of the studies were conducted in shallow ground water underlying coarse-textured soils and thus represent a worst-case scenario for ground water contamination in aquifers consisting of unconsolidated geologic deposits. The results cannot be directly applied to bedrock settings, particularly situations involving karst and fractured rock. We have also chosen, in many cases, to compare ground water quality from feedlots to ground water quality in areas where sampling occurred, rather than compare data directly with water quality criteria. This represents somewhat of a comparative risk approach, which we feel is more appropriate considering ground water impacts from row crop agriculture. Most sampled feedlots were in areas with row crop agriculture.

The paper provides an abbreviated version of the comprehensive report *Effects of Liquid Manure Storage Systems on Ground Water Quality*. A companion fact sheet provides a short, non-technical discussion of our work with feedlots.

We chose to organize the discussion by different types of manure storage systems. Because there may be several ground water monitoring studies for a particular storage system, abstracts are provided at the beginning of each section. This organization makes it difficult to compare ground water quality under different manure storage systems. We therefore included a section that provides a discussion of these comparisons. The Executive Summary is organized by the different studies we conducted.

Some referenced MPCA reports and data collected for this report are found on our website:

http://www.pca.state.mn.us/water/groundwater/gwmap/index.html

We have attempted to provide an accurate analysis and interpretation of the information collected from our studies. As with any large dataset and lengthy report, there are likely to be errors. Significant errors and omissions can be forwarded to us.

Executive Summary

Research on ground water impacts from liquid manure storage has increased in recent years, but there are still information gaps. The Minnesota Pollution Control Agency (MPCA) conducted a variety of ground water monitoring studies between 1994 and 2000 at various manure storage facilities to help fill these data gaps.

Study 1

The first study, conducted in 1999 and 2000, consisted of sampling ground water adjacent to manure storage systems ranging in age from six to 40 years, with a median age of 20 years. We sampled four distinct types of manure storage. These included 1) open feedlots with no liquid manure storage, 2) feedlots with liquid storage but no cohesive soil liner or other type of constructed liner (unlined basins)[1], 3) feedlots with liquid storage and compacted soil liners (earthen-lined basins), and 4) feedlots with liquid storage and concrete-lined basins. We sampled a minimum of three feedlots within each of these feedlot types.[2] The selected sites represent the range in manure storage types encountered at feedlots in Minnesota.

Sampling at each site consisted of installing 8 to 24 temporary wells. Most of these wells were screened within five feet of the water table. At each site, we typically drilled one or two wells up-gradient of the manure storage basin. The remaining wells were either drilled side-gradient or down-gradient of the manure storage system in an attempt to define a ground water plume associated with the manure storage. At each well, we collected field measurements of temperature, pH, dissolved oxygen, alkalinity, oxidation-reduction potential, and specific conductance. At each well, we collected samples for laboratory analysis of major ions, ammonia, Kjeldahl nitrogen, organic carbon, *E. coli* bacteria, and phosphorus.

Coarse-textured soils existed at each site. Most samples were collected from the upper five feet of ground water. Consequently, results for this study represent a worst-case scenario, since we sampled in hydrogeologic settings considered most vulnerable to contamination of ground water.

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[1] See Glossary for definitions.

We observed wide-ranging impacts at different sites. There was evidence of shallow ground water contamination down-gradient of manure storage areas at each site. The down-gradient distance in ground water to which impacts were observed was less than 100 feet for concrete-lined systems, 200 to 300 feet for open lots and earthen-lined systems, and several hundred feet for unlined systems. Evidence of impacts included higher concentrations of ammonia-nitrogen, organic nitrogen, organic carbon, phosphorus, chloride, and potassium in down-gradient versus up-gradient wells. Nitrate-nitrogen is a chemical of potential concern when ammonia-nitrogen is converted to nitrate in the presence of oxygen. We observed elevated concentrations of nitrate-nitrogen in down-gradient wells at some sites.

Concentrations of chemicals varied widely between types of storage systems. The table below summarizes important results.

Site Type	**Excess Nitrogen (mg/L)**		**Excess Phosphorus (mg/L)**	**Plume Distance (feet)**
	50 feet[1]	100-200 feet[2]		
Open feedlot	23	12	0.10	200
Unlined basin	284	11	7	300
Earthen basin	33	13	2	200
Concrete basin	13	2.4	1.2	100

[1] At a distance of 50 feet down-gradient from the manure storage area
[2] At a distance of 100 to 200 feet down-gradient from the manure storage area

Nitrogen is one chemical that can adversely impact surface water or drinking water in wells. The MPCA Aquatic Life Standard (surface water criteria) for ammonia is 0.040 mg/L and the MDH Health Risk Limit (drinking water criterion) for nitrate is 10 mg/L. To assess potential impacts from nitrogen down-gradient of manure storage systems, we calculated total nitrogen additions to ground water (excess nitrogen) from the storage systems. We defined excess nitrogen as the difference in total nitrogen concentration between down-gradient and up-gradient wells. Positive values indicate nitrogen loading from the manure storage areas. Median excess nitrogen concentrations in down-gradient wells within 50 feet of manure storage areas were 284 mg/L for unlined basins, 23 mg/L for open lots, 33 mg/L for earthen-lined basins, and 13 mg/L for

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[2] Sites with unlined basins and some sites with compacted earthen basins do not meet current state

concrete-lined basins. Median excess nitrogen in wells 100 to 200 feet down-gradient of the manure systems were 11 mg/L for unlined basins, 12 mg/L for open lots, 13 mg/L for earthen-lined basins, and 2.4 mg/L for concrete-lined basins. We estimate manure storage systems should not cause exceedances of surface water criteria for ammonia-nitrogen and drinking water criteria for nitrate-nitrogen when distances to a surface water body or a well are more than 100 feet for concrete-lined basins, 200 feet for earthen-lined basins or open lots, and 300 feet for unlined basins. These distances may not be appropriate for storage systems located in coarse-textured soils and underlain by a deep water table. Under these conditions, much of the excess nitrogen may occur as nitrate, which is mobile in ground water.

Phosphorus in ground water is a concern when ground water discharges to surface water and phosphorus concentrations cause excess algae growth in surface water. We defined excess phosphorus as the amount of phosphorus loading attributable to the manure storage area at a feedlot. Excess phosphorus in down-gradient wells within 50 feet of manure storage areas was 7.0 mg/L for unlined basins, 2.0 for earthen-lined basins, 1.2 mg/L for concrete-lined basins, and 0.10 mg/L for open lots. Excess phosphorus approached zero 100 feet down-gradient of most manure storage areas. Average total phosphorus concentrations in central Minnesota lakes are 0.050 mg/L.[3] Manure storage systems located 100 feet or more away from surface water should not impact lakes or rivers, although excess phosphorus at one unlined site was more than 0.5 mg/L 250 feet from the manure basin.

Study 2

In the second study, ground water monitoring networks were established at 17 feedlots between 1994 and 1998. Each site had no prior history of manure storage. Thirteen basins consisted of earthen-lined systems and four had concrete liners. Storage capacity of each basin was several million gallons.

Private consultants were hired by individual feedlot owners to install and sample the monitoring networks and submit data to the MPCA. There are three to six wells at

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requirements for manure storage.

the 11 sites with monitoring wells. Tile lines surround manure basins at 12 sites. Samples were collected from wells and tile lines prior to addition of manure. Quarterly sampling in wells occurred at most sites following addition of manure to the storage basins. Quarterly sampling occurred in tile lines when water was flowing through the tiles. At the sites with earthen liners, we observed statistically significant positive correlations between sampling event and the concentration of one or more indicator (see Glossary for definition) at seven sites and either no correlation or a negative correlation at six sites. There was limited data for analysis at the four sites with concrete liners. Positive correlations were associated with decreases in the ground water oxidation-reduction potential down-gradient of the manure basin. While these changes may reflect impacts from a manure basin, we observed a positive correlation with nitrogen at only one site. The results are inconclusive, partly because of the small sampling period (less than five years) and the lack of land use information, which confounds our ability to interpret water quality data. Continued monitoring is needed before a rigorous trend analysis can be conducted.

Study 3

A third study consisted of water monitoring beneath three earthen-lined manure basins. Lysimeters capture leachate passing through the cohesive, soil-lined bottom and sidewalls of these basins, allowing measurements of flow rate and analysis of leachate water quality. The lysimeters were installed in the mid-1990's by the United States Geological Survey, Natural Resources Conservation Service, University of Minnesota, local Soil and Water Conservation Districts, and the MPCA. The lysimeter sampling has been a collaborative effort by the USGS, MPCA, and University of Minnesota. Initial results indicate elevated concentrations of chloride and elevated specific conductance in leachate through sidewalls compared to bottoms of the basins. Concentrations of nitrogen and phosphorus in leachate were relatively low. Because nitrogen (as ammonia or in organic forms) and phosphorus are less mobile than chloride, it may take several

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[3] Data are from the MPCA web page: http://www.pca.state.mn.us/water/pubs/lwqar.pdf

additional years of monitoring before we can accurately assess trends in concentrations of these chemicals in ground water.

Study 4

A fourth study consisted of monitoring an open feedlot where an earthen manure storage basin with a plastic, geosynthetic, bentonite clay liner was installed in 1997. The liner was covered with 1 foot of native soil. A filter strip was also constructed down-gradient of the animal barns. Quarterly monitoring since 1998 shows total nitrogen[4] concentrations in ground water beneath the feedlot decreased by 55 percent in the three years since construction. Concentrations of phosphorus and organic carbon have also decreased beneath the feedlot. With only three years of data, we cannot separate the effects of removing the open lot versus installing the new basin and the filter strip.

Summary

Results from our studies indicate unlined manure basins have greater impacts on ground water quality than open feedlots or earthen- and concrete-lined storage systems. Concrete-lined basins appear to have minor impacts to ground water even when placed over coarse-textured soils. Cohesive soil-lined basins (earthen liners) and open lots impact ground water, but impacts vary widely from site to site.

Impacts from manure storage areas are limited to relatively discrete plumes extending down-gradient from the manure storage area. These plumes have widths similar to the width of the manure storage area and lengths that vary depending on the amount of seepage and hydraulic properties of the aquifer. Because of the limited extent of ground water impacts, manure can be managed to minimize impacts to ground water. In cases where concrete-, geomembrane-, or geosynthetic-lined systems cannot be installed due to economic considerations, setback distances can be utilized to minimize the potential exposure for surface water or drinking water receptors.

The MPCA will continue monitoring sites and analyzing for trends with permanent monitoring networks and leachate collection systems. Sampling parameter

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[4] Total nitrogen is the sum of nitrate-nitrogen, Kjeldahl nitrogen, and ammonia-nitrogen.

lists at some sites may be expanded to include viruses, antibiotics, and growth hormones. We will look for additional monitoring sites with new concrete-lined or geosynthetic-lined systems.

Introduction

Properly constructed manure storage systems minimize water quality impacts of manure. Chemicals such as ammonia, organic carbon, chloride, and phosphorus, however, often leach from storage systems to ground water. Concentrations of ammonia, chloride, and phosphorus could potentially exceed water quality criteria or guidelines[5], while organic carbon may impact the fate of microorganisms and other chemicals. Numerous studies describe ground water impacts from liquid manure storage systems, but few reports consolidate information from different studies. There are many reports and manuals providing information on manure storage system design, and many of these reports provide information on seepage through manure storage systems.

The Minnesota Pollution Control Agency (MPCA) conducted ground water monitoring at several feedlots in Minnesota between 1994 and 2000. This monitoring can be divided into four studies. The first investigation was a study initiated in 1998 to assess ground water impacts at feedlots that have manure storage systems older than five years. All of these feedlots are located on coarse-textured soils, where potential leaching of liquid manure is greatest. The objectives of this study were to

- determine if leachate from manure storage systems reaches ground water;
- compare ground water impacts from different types of manure storage systems; and
- assess the environmental contamination risk to ground water associated with storage of livestock manure.

The second study consisted of monitoring at sites with newly constructed, earthen- or concrete-lined manure storage systems. These are systems installed in areas with no previous history of manure storage, although manure may have been applied to agricultural fields in these areas. Monitoring wells exist at sites on coarse-textured soils where artificial drainage is not required. Tile lines and monitoring wells are used to monitor water quality at sites on poorly drained soils where artificial drainage is required

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[5] Chloride has a Secondary Maximum Contaminant Level of 250 mg/L for drinking water; ammonia has a Lifetime Health Advisory level of 39 mg/L for drinking water and a chronic Aquatic Life Standard of 0.040 mg/L for Class 2B surface waters; phosphorus does not have criteria, but MPCA (2001) has established values that may be used as guidelines for phosphorus concentrations in lakes.

to lower the water table. Sampling at most of these facilities began in 1994 and 1995. Private consultants typically collect samples at these sites.

The third study includes monitoring the quantity and quality of leachate beneath three earthen liners with leachate collection systems. This study began as a joint effort between the Natural Resource Conservation Service (NRCS), the United States Geological Survey (USGS), and the MPCA. The MPCA assumed monitoring responsibilities for the three sites in 1998. A report prepared by Ruhl (1999) summarizes first-year results for two of the sites.

The fourth study consisted of monitoring changes in ground water quality adjacent to an open feedlot where a new manure management system was installed. The objective of this study was to monitor changes in water quality after removal of the open lot and monitor water quality beneath the new system, which consists of an earthen manure storage basin with a 0.25 inch geosynthetic, bentonite clay liner, covered with 1 foot of native soil.

The following discussion is organized by types of manure storage system. We first introduce the chemistry of manure and discuss different types of storage systems.

Chemistry of Manure

Table 1 summarizes chemical information for solid and liquid fractions of manure.[6] Data in Table 1 represent only a few sources of information on manure chemistry. There is large variability in the chemistry of manure from farm to farm. Nevertheless, the data indicate high concentrations of nitrogen, organic carbon, phosphorus, chloride, and potassium in solid manure. Concentrations in the liquid fraction are much lower, but concentrations of ammonium and total nitrogen are still two to three orders of magnitude greater than natural background concentrations in ground water (MPCA, 1999a). Concentrations of chloride and potassium in liquid manure are one to two orders of magnitude greater than natural background concentrations found in ground water. Concentrations of coliform bacteria are also high in liquid manure.

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[6] The liquid fraction is the liquid that separates from the solid material in the storage system.

Consequently, manure in either form has the potential to adversely impact ground water quality.

Types of Storage Systems for Liquid Manure

The objectives of lined manure storage systems are to prevent overland runoff of manure (by containing manure in an enclosed basin) and minimize leaching of manure to ground water until the manure can be used as a fertilizer on cropland. Manure solids accumulate at the base of storage basins and form an organic seal at the manure-soil interface. The conductivity of this seal is 10^{-6} cm/s or less (Roswell et al., 1985; Miller et al., 1985; Parker et al., 1994; Maule and Fonstad, 1996; Fonstad et al., 1995). Required standards are about 10^{-7} cm/s. Soil texture, type of liner (concrete or earthen), and depth of water in the basin (Fonstad and Maule, 1995; Barrington et al., 1987; Roswell et al., 1985; Barrington and Madramootoo, 1989) typically have less impact on final infiltration rates than the organic seal. In many storage systems, however, preferential pathways for seepage may develop due to freezing and thawing, animal burrowing, or poor construction. These reduce the effectiveness of the organic seal in minimizing seepage (McCurdy and McSweeney, 1993).

	Solid					**Liquid**			**Ground water**
Chemical	**Cattle**	**Dairy**	**Dairy**	**Hog**	**Hog**	**Dairy**	**Hog**	**Hog**	
	mg/kg (dry weight basis)					mg/L			mg/L
Total phosphorus	79500	6188	6673	-	13350	-	-	-	0.056
Organic matter	283500	621000	-	-	-	-	-	-	2.4\
Total nitrogen	15800	41436	40037	-	10600	420	1500	778	-
Sodium	3934	-	-	-	613	-	-	-	4.98
Calcium	1413	-	-	-	-	-	-	71	74.2
Sulfate	3082	-	-	-	-	-	-	-	4.25
Chloride	8447	9061	-	-	4440	215	300	-	5.81
Ammonium	3488	14586	13346	2628	4550	165	1000	679	0.050
Nitrate	496	-	-	28	10	1.5	2	1	< 0.50
Potassium	-	31492	40037	1513	2900	-	-	340	1.78
	Colonies per 100 mL								
Fecal coliform	-	-	-	-	-	10000	29000	-	-
Reference	Chang et al	Comfort et al	Motavalli	Maule & Fonstad	Fonstad & Maule	Ruhl	Ruhl	Ham et al.	MPCA 1998a,b

[1] Concentration is for total organic carbon

Table 1: Median concentrations of chemicals in solid and liquid manure.

We divided manure storage systems into several types. First are open feedlots, in which solid manure is distributed across the soil surface in small, confined spaces. Although this is not a true storage system, the soil surface acts as the storage system. The upper few inches of soil mix with manure and this upper soil layer is often greatly compacted. Unlined liquid manure storage basins represent a second type of storage system. There is no attempt to restrict leaching through these systems by constructing bottom or sidewall liners. Unlined systems often consist of simple basins excavated into native soils or lowland areas where manure is deposited. Unlined systems have generally not been permitted on medium- or coarse-textured soils in Minnesota. A third type of system is manure basins with cohesive soil liners (earthen liners). Earthen liners consist of low permeability material, such as cohesive clay, that is compacted. The MPCA established design requirements for earthen manure storage basins, in 1991 as guidelines and currently in rules (Minnesota Rules, Chapter 7020). These include specifications for type of soil used in liners, thickness of the liners, elevation above the seasonal high water table or above karst bedrock, side slope requirements, and minimum requirements for compaction of the liner material. A fourth type of system includes basins with poured concrete liners. The fifth group of system includes basins with synthetic and bentonite liners. Synthetic liners consist of flexible plastics that have very low permeability and are more resistant to weathering or damage than earthen liners. They are often used in conjunction with earthen liners.

METHODS AND MATERIALS

We utilized a variety of monitoring techniques to assess ground water impacts from manure storage systems. These included use of temporary wells, permanent monitoring wells, tile lines, and lysimeters that capture flow beneath or down-gradient of manure storage systems.

Temporary Well Investigations

We sampled twelve sites using direct push technology to install temporary wells. Table 2 summarizes characteristics of these sites. Figure 1 illustrates the locations of the sites. This method consists of installing a small diameter well, collecting a sample, and then properly sealing the well. The method is useful for conducting site investigations because many samples can be collected in a short time period. Field kits for analyzing chemical concentrations are often used in conjunction with temporary wells because real time information can be valuable for placement of additional wells. A small site such as a feedlot can be investigated in two or three days using this technology.

Site	Storage system	Type of animal	Animal units	Age of storage system (years)	Soil	Depth to water (ft)
O1	Open feedlot	Beef	700	20	Coarse sand and gravel	7 to 15
O2	Open feedlot	Beef	300	20	Coarse sand	15 to 20
O3	Open feedlot	Dairy	100	40	Loamy sand	10 to 15
O4	Open feedlot	Hog	50	More than 20	Coarse sand	12
U1	Unlined basin	Hog	250	25	Coarse sand and gravel	15 to 25
U2	Unlined basin	Hog	250	13	Coarse sand	2 to 6
U3	Unlined basin	Hog	50	More than 20	Coarse sand	12
E1[1]	Earthen liner	Dairy	150	10	Coarse sand/gravel	8 to 15
E2	Earthen liner	Dairy	130	6	Sand	30 to 40
E3	Earthen liner	Dairy/beef	175	12	Sandy loam	45 to 55
C1[1]	Concrete liner	Hogs	815	10	Coarse sand and gravel	15 to 20
C2	Concrete liner	Hogs	500	10	Coarse sand and gravel	15 to 20

[1] Two storage systems exist at the site

Table 2: Summary of sites sampled with temporary wells.

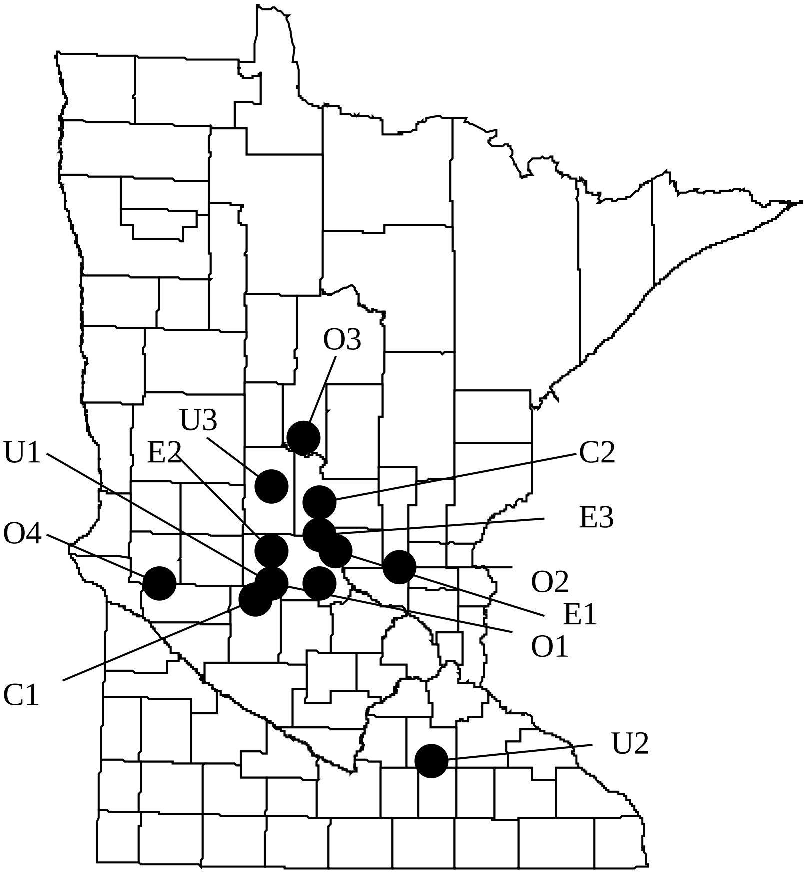

Figure 1: Location of sites with temporary wells.

At each site, we first established general ground water flow direction by triangulating the first three temporary wells and measuring elevations relative to a fixed reference. Accuracy of water elevations was 0.1 foot. We then installed additional temporary wells to define the extent and magnitude of impacts from a manure basin or open feedlot. Water levels were measured in each well to better define ground water flow at each site and help locate additional wells. Drilling ceased when impacts to ground water were no longer evident or when additional wells could not be installed for logistical reasons. Continuous soil samples, collected during well installation, provided information on soil texture between the land surface and the top of the water table.

Wells consisted of a 1.25 inch diameter, steel probe rod with a stainless steel, 0.010 slot, 4 foot temporary screen. We collected samples from the top 2 feet of the water table with a fully exposed screen. In deeper, nested wells, where a discrete sample was required, the screened interval was 1 to 2 feet. A peristaltic pump pulled water through 3/8 inch polyethylene tubing inserted through the probe rod to the bottom of the screen. Water was pumped through a flow cell in which specific conductance, pH, oxidation-reduction potential, temperature, and dissolved oxygen were measured continuously with a multi-parameter probe. Sample collection occurred when field readings of temperature, pH, and specific conductance stabilized. Stabilization criteria were 0.1 pH unit, 10 percent for specific conductance, and 0.1 ^{o}C for three consecutive readings. Samples for laboratory analysis included major cations and anions, ammonia-nitrogen, Kjeldahl-nitrogen, dissolved organic carbon, and fecal coliform bacteria. Samples were stored in a cooler at 4^{o}C until delivered to the laboratory within appropriate holding times. Field-measured specific conductance or chloride concentrations more than twice the value observed in the up-gradient well(s) indicated impacts from the feedlot.

Decontamination procedures for bacteria samples included scrubbing the screen, screen sheath, and any probe rod or connections that intersected the water column with tap water and then a bleach solution (approximately one cup bleach per five gallons water). The equipment was then rinsed with deionized water. Sampling tubing was discarded after each use. Latex gloves were worn during sampling.

Appendix I summarizes laboratory analysis methods and reporting limits. We did not sample each site for all of the chemicals listed in Appendix I. Samples for inorganic chemicals and organic carbon analysis were delivered to the University of Minnesota Soil Science Analytical Laboratory in St. Paul. Samples for fecal coliform analysis were sent to the Minnesota Department of Health Laboratory in Minneapolis. Quality Assurance/Quality Control procedures included 10 percent field duplication, 10 percent laboratory duplication, acid blanks, and cation-anion balance. All duplicates were within acceptable limits. MPCA (1998c) summarizes field sampling methods.

Permanent Monitoring Investigations

Producers intending to construct new manure storage basins are required to first obtain a permit from the MPCA. During the MPCA environmental review process for new feedlots, some producers volunteered to conduct ground water monitoring. At other sites, the MPCA required ground water monitoring as a condition in the permit. The monitoring was required largely due to the size of the basin. MPCA initiated monitoring at these sites to provide information on environmental effects of large basins in Minnesota.

Monitored basins are lined with either cohesive soil constructed out of native soil materials at the construction site, or with poured concrete. Table 3 summarizes characteristics of each site. Figure 2 illustrates the location of each site. The storage systems have a design capacity that ranges between 3 and 10 million gallons, and are between 10 and 14 feet deep when filled to capacity. The manure basins are constructed partly below and partly above ground. Soils at the sites are primarily clays or sandy clays, although lenses of sand or clayey sand occur at some sites.

All manure storage system designs were developed by private engineers licensed in Minnesota. Basins with earthen liners were constructed using a compacted cohesive soil liner that was a minimum of 2 feet thick. The liners were designed and constructed so that theoretical seepage rates would be less than 1/56 inch per day (2.1×10^{-7} cm/s), assuming the basin was filled to capacity and there was no biophysical sealing by manure at the soil/manure interface. To meet the maximum designed seepage rates, the conductivity of the liner must be less than 1×10^{-7} cm/sec. At sites with evidence of past or current saturated soil, tile line drainage systems were placed at least two feet below the liner around the perimeter of the basins.

Feedlot owners and their consultants developed the monitoring plans. MPCA approved monitoring plans prior to sample collection. Perimeter tile lines and monitoring wells were installed and sampled two or three times prior to adding manure to the basins.

Site	Type of Basin	Approx. Date Manure Added	Livestock	Animal Units	Wells	Tile lines
EM1	Earthen	10/94	Hogs	4800	X	
EM2	Earthen	9/94	Hogs	2338	X	
EM3	Earthen	9/94	Hogs	3040	X	X
EM4	Earthen	12/94	Dairy	700	X	
EM5	Earthen	11/94	Hogs	4800	X	X
EM6	Earthen	4/95	Hogs	-	X	
EM7	Earthen	4/95	Hogs	-	X	
EM8	Earthen	8/95	Hogs	-	X	X
EM9	Earthen	9/94	Hogs	-	X	X
EM10	Earthen	7/94	Hogs	-	X	X
EM11	Earthen	12/95	Dairy	700		X
EM14	Earthen	1997	Hogs	-		X
EM15	Earthen	1/95	Hogs	8000		X
EM16	Earthen	4/96	Hogs	4800		X
CM1	Concrete	8/97	Hogs	-		X
CM2	Concrete	8/97	Hogs	-		X
CM3	Concrete	8/97	Hogs	-		X
CM4	Concrete	Fall, 1997	Hogs	-	X	

Table 3: Summary information for sites with permanent monitoring networks.

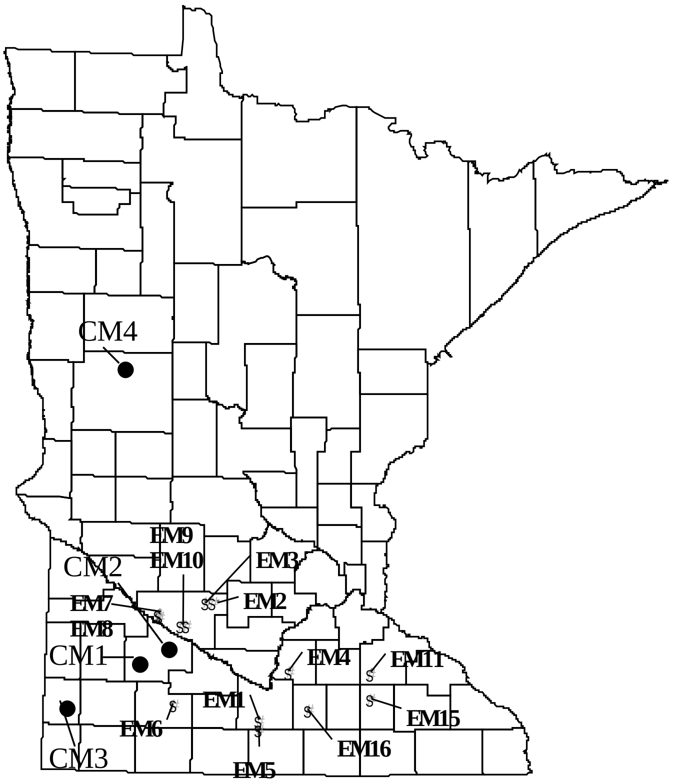

Figure 2 : Location of sites with permanent monitoring networks.

Quarterly sampling occurred following addition of manure. Sample parameters included nitrate, ammonia, Kjeldahl nitrogen, chloride, sulfate, and fecal coliform bacteria. Individual consultant reports describe well installation and sampling procedures. MPCA reviews and approves these reports, as well as modifications to monitoring plans.

At two sites, MPCA installed permanent monitoring networks. In 1997, an earthen manure storage basin with a geosynthetic, bentonite clay liner was installed at a site in Isanti County. The liner was covered with 1 foot of native soil. The site was an open feedlot for more than 20 years. After drilling several temporary wells to determine ground water flow and water quality, we installed eight permanent wells in autumn of 1997. We began quarterly sampling of these wells in 1998. At another site, in Otter Tail County, we installed four permanent wells adjacent to a concrete-lined manure basin. The site had no prior history of manure storage. The basin was constructed in 1997. We began quarterly monitoring in 1998. Sampling parameters at both sites include major ions, organic carbon, fecal and total coliform bacteria, Kjeldahl nitrogen, ammonia, and trace inorganic chemicals. MPCA (1998a) describes well construction methods.

Leachate Collection Systems

Two separate projects were initiated by the Minnesota Pollution Control Agency to collect seepage waters which move through a large portion of a cohesive soil liners and measure the volume and chemistry of these seepage waters over time. The first project, begun in 1993, is a cooperative effort by the Natural Resources Conservation Service, University of Minnesota, Morrison County and the Minnesota Pollution Control Agency. The farm chosen for the study was a 100 cow dairy operation in central Minnesota, where a 600,000 gallon earthen basin (130’x115’ top dimensions) was to be constructed during the fall of 1993. The glacial till at the site was classified as sandy clay and silt loam soils.

Following excavation of the basin, and prior to construction of the cohesive soil liner, a 35’X70’ geomembrane was installed in a position to separately collect seepage waters from a portion of the basin bottom and a portion of the sidewall. The purpose of the geomembrane was to intercept liquids that pass through the cohesive soil liner and route these seepage waters to a collection sump located at the side of the basin. A blanket of sand was placed on top of the geomembrane to act as a drainage material and the cohesive soil liner was then constructed on top of the sand blanket. The liner is two feet thick on the bottom and was constructed in ten-foot wide horizontal lifts on the sidewall. The macro-lysimeter was visited every 2 to 3 weeks during the first five months of operation and was sampled approximately 9 times per year from 1994 to 1997. Seepage water samples are taken during site visits and analyzed at a laboratory for nutrients and other major cations and anions.

Macrolysimeters similar to the one in Morrison County were constructed in 1997 at a swine facility in Dodge County and a dairy facility in Nicollet County. These projects were a collaborative effort of the U.S. Geological Survey, the Natural Resources Conservation Service and the Minnesota Pollution Control Agency. The macrolysimeter design is reported in Swanberg (1997). The first year of data was collected by the U.S. Geological Survey and is reported in Ruhl (1999). Collection of data in 1999 and 2000 by the MPCA has been sporadic.

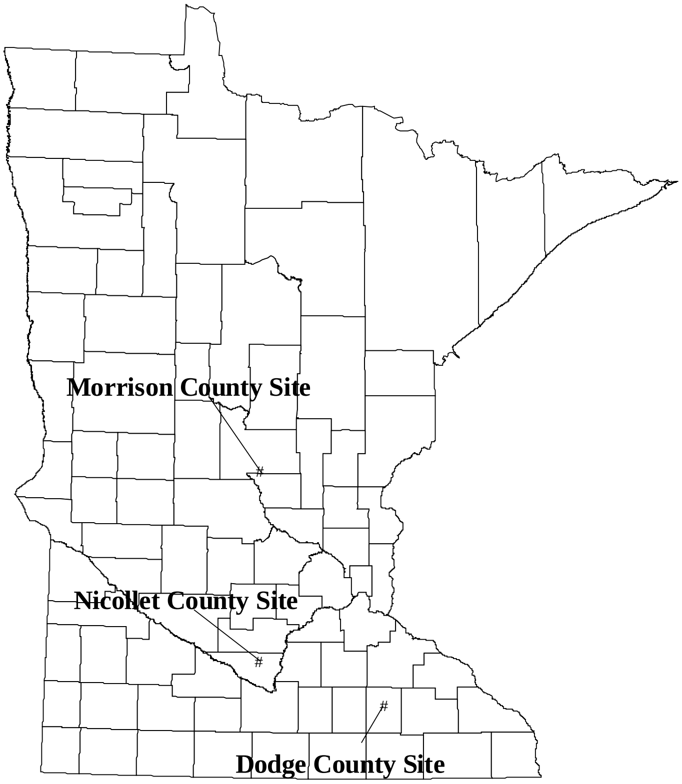

Figure 3: Location of sites with lysimeters.

Data Analysis

MPCA (1998d) describes statistical methods used in this report. The Risk Based Site Evaluation guidelines (MPCA, 1998e) describe methods for assessing human and ecological risk associated with contamination at feedlots.

Statistical methods for the first study, in which temporary wells were used, included the Kruskal-Wallis test for comparing concentrations between treatments and the Spearman rank method for correlation analysis. We used a significance level of 0.05 to identify significant differences between groups or to identify significant correlations. We developed a ranking procedure to assess relative impacts from each manure storage system. For each site, ranks were assigned from lowest to highest concentration for potassium, phosphorus, organic carbon, ammonia, chloride, and iron, and from highest to lowest for nitrate, dissolved oxygen, and Eh. We employed group tests (Kruskal-Wallis test) to the ranks to compare ranks between individual wells at a site. Wells with high ranks were assumed to be impacted by the feedlot, while wells with low ranks were not impacted. This method fails when the chemicals used in the ranking process are not indicators of impacts from a feedlot. For example, at sites with thick unsaturated zones beneath a manure storage basin, saturated flow does not occur. Consequently, nitrogen occurs as nitrate, rather than in reduced forms (ammonia or organic nitrogen). In these cases, the ranking procedure required modification. These modifications are described in appropriate sections of the report.

At sites with temporary wells, we estimated plume lengths by comparing concentrations of chloride, specific conductance, and organic carbon in down-gradient wells with concentrations in up-gradient wells. If down-gradient concentrations of these three indicators were two or more times greater than concentrations in up-gradient wells, we assumed water quality was impacted by the manure storage system. If one down-gradient well was impacted and the next well down-gradient was not, we assumed the plume extended halfway between the two wells.

For sites with permanent monitoring wells, we compared chemical concentrations in up- and down-gradient wells using tolerance limits. This analysis is described in Loftis et al. (1987). Prior to calculating tolerance limits, we determined if the differences in concentration between up- and down-gradient wells were distributed normally. If the data were not distributed normally, we calculated nonparametric tolerance limits. In some cases where we had collected sufficient information prior to addition of manure to a storage basin, we calculated 90th percent confidence intervals for chemical concentrations in a well. We then compared these results with data from the well following addition of manure.

In both permanent monitoring wells and perimeter tiles, we analyzed for correlation between chemical concentration and sampling event using the Spearman rank method. Correlation analysis was also performed between chemical concentrations and flow rate in tiles, if sufficient flow information existed. A significance level of 0.05 was used to identify significant correlations.

RESULTS AND DISCUSSION

Open Feedlots

Most open lots in the Minnesota consist of small areas, less than five acres, where animals are confined. The upper 15 cm (6 inches) of soil are compacted in these high traffic areas. Soils at an open feedlot are subject to cracking, shrinking, or swelling. With no protective layer below the soil surface, water seeping through the upper 6 inches of soil travels quickly to ground water.

Table 4 shows maximum concentrations in down-gradient wells at each of the four sites with open feedlots. Estimates of plume length are included in the table. Plumes at sites O1 and O3 extended for distances of more than 400 feet and were nitrate-reducing over most of their length. Plumes at Sites O1 and O3 were characterized by high concentrations of ammonia, organic nitrogen, and organic carbon, occasionally high concentrations of phosphorus, chloride, and potassium, and low concentrations of dissolved oxygen and nitrate. Concentrations of ammonia, phosphorus, organic nitrogen, and organic carbon decreased along the length of the plume. If oxidizing conditions were encountered at the down-gradient edge of these plumes, the quantity of nitrogen remaining would not be sufficient to result in nitrate concentrations exceeding the drinking water standard. The concentrations of phosphorus and ammonia in ground water, however, represent potential concerns for surface water that intersects a plume.

At Sites O2 and O4, plumes were characterized by high concentrations of nitrate. Concentrations of organic carbon and reduced nitrogen were similar in down- and up-gradient wells. Leaching mechanisms are unclear, but oxidizing conditions exist beneath the two feedlots. Typical chemicals used to identify plumes were poor indicators at these two sites. Plumes extended at least 100 feet and probably much more, considering the mobility of nitrate. Nitrate concentrations represent a potential concern for drinking water receptors down-gradient of the feedlot at Site O2.

		Maximum down-gradient concentration (mg/L)				
Site	**Approximate plume length (ft)**	**Ammonia**	**Total Kjeldahl nitrogen**	**Phosphorus**	**Total organic carbon**	**Potassium**
O1	425	3.88	7.27	0.191	28.9	45.2
O2	More than 220	1.01	0.52	-	3.70	-

O3	400	35.9	44.9	0.890	200	672
O4	More than 100	0.10	0.63	0.055	4.7	6.3

Table 4: Approximate plume lengths and maximum concentrations of selected chemicals at the three open lot sites.

Manure Storage Basins Constructed without a Soil Liner

Manure storage basins constructed without a permit were often unlined. These may have simply been excavated holes in the ground or natural depression areas where manure was stored. The amount of leaching to ground water is often greater for an unlined system compared to a permitted lined system (Maule, 1995).

Table 5 summarizes estimated plume length and maximum chemical concentrations in wells down-gradient of unlined manure storage basins. Concentrations of reduced nitrogen are very high in wells down-gradient of unlined basins. Concentrations of ammonia and phosphorus represent a potential concern if the plume containing liquid manure leachate intersects a surface water body. Concentrations exceed surface water criteria in down-gradient wells closest to the basins. Phosphorus exceedances did not extend more than 100 feet down-gradient of the basins, but ammonia exceedances extended for more than 200 feet.

Site	**Approximate plume length (ft)**	**Maximum down-gradient concentration (mg/L)**				
		Ammonia	**Total Kjeldahl nitrogen**	**Phosphorus**	**Total organic carbon**	**Potassium**
U1	More than 320	265	374	1.10	74.5	181
U2	450	136	153	8.06	45	105
U3	More than 125	163	188	3.56	25.2	-

Table 5: Approximate plume lengths and maximum concentrations of selected chemicals at the three sites with unlined basins.

Manure Storage Basins Constructed with a Cohesive Soil Liner

Cohesive soil or earthen-lined pits or basins are the most common manure storage system for dairy and beef cattle operations. They are less expensive to construct than systems with concrete, geosynthetic, or geomembrane liners. Seepage rates through the compacted earthen walls are generally much lower than through native soil. In this section, we discuss results from three different studies of earthen-lined systems in Minnesota.

In the first study, we selected three sites with manure basins older than five years. Table 6 shows maximum concentrations of ammonia, Kjeldahl nitrogen, phosphorus, potassium, and organic carbon in down-gradient wells. Estimates of plume length are included in Table 6. Plumes down-gradient of earthen-lined systems varied in water quality. An important factor appears to be whether nitrate-reducing conditions develop beneath the manure basin. At Site E1, nitrate-reducing conditions were observed beneath and down-gradient of the two manure basins. Concentrations of ammonia and organic nitrogen were high down-gradient of the basins. At Sites E2 and E3, nitrate concentrations down-gradient of the manure basins exceeded concentrations in up-gradient wells. At Sites E2 and E3, unsaturated zone thickness exceeded 20 feet. Because of the thick unsaturated zones, ammonia may be converted to nitrate. Nitrate is mobile in water and nitrate plumes developed at these two sites.

Plumes extended for distances of 250 to over 400 feet. In plumes with nitrate-reducing conditions, concentrations of ammonia, phosphorus, organic nitrogen, and organic carbon decreased along the length of the plume. In plumes lacking nitrate-reducing conditions, nitrate and chloride concentrations decreased along the length of the plume, but nitrate concentrations remained above background concentrations more than 300 feet from the storage system.

Storage systems similar to those at Sites E2 and E3 have the potential to impact drinking water receptors due to high nitrate concentrations. Storage systems similar to those at Site E1 represent a potential concern for ammonia and phosphorus if ground water discharges to an adjacent lake or river.

		Maximum down-gradient concentration (mg/L)				
Site	**Approximate plume length (ft)**	**Ammonia**	**Total Kjeldahl nitrogen**	**Phosphorus**	**Total organic carbon**	**Potassium**
E1: basin 1	275	66.2	76.9	1.53	40.9	53.8
E1: basin 2	400	4.17	7.1	3.66	50.1	200.6
E2	325	0.13	0.76	0.06	3.9	9.29

E3	320	4.81	7.39	1.26	39.2	6.07

Table 6: Approximate plume lengths and maximum concentrations of selected chemicals at the sites with earthen liners.

In the second study, we established permanent monitoring wells exist at ten sites with newly constructed earthen-lined manure storage systems. Five of these sites also have tile lines surrounding the manure storage system. An additional four sites have just tile lines. Each site had no previous history of animal operations. Sampling at each site occurred two or more times prior to addition of manure to the storage systems. Following addition of manure, quarterly sampling was planned at each of the sites.

Table 7 indicates, evidence of impacts at one site, positive correlations between concentration of one or more chemical and sampling event at seven sites, and no correlation or negative correlations at four sites. Data from two sites did not support conclusions regarding correlation between concentration and sampling event. An impact means there is statistical evidence that concentrations of one or more chemical is greater in down-gradient wells than in up-gradient wells. A correlation means that the concentration of an indicator chemical has significantly increased or decreased with sampling event in down-gradient but not up-gradient wells.

The results should be viewed with caution, for several reasons. First, many of the sites with tile lines had incomplete data because tile lines did not flow throughout the monitoring period. Second, there are only five years of data for most sites. Concentration trends often take longer than this to become evident, particularly considering chemicals such as phosphorus and ammonia, which are less mobile than chemicals such as nitrate and chloride. With no information on ground water flow rates, it is difficult to estimate when trends might begin to develop. Third, significant positive correlations at most sites were due to changes in the oxidation-reduction characteristics of ground water down-gradient of the manure storage basin. The observed changes are typical of changes resulting from seepage of liquid manure, but these changes alone do not indicate a potential risk to surface water or drinking water receptors. Site EM15 was the only site where we observed positive correlations between nitrogen concentration and sampling event. Fourth, the monitoring networks were not designed for rigorous statistical analysis. Factors such as seasonality and spatial correlation are difficult to assess. Finally, tolerance limits may not represent the best statistical tool for comparing up- and down-gradient wells. Gibbons (1999) discusses an alternative method for assessing an increase in chemical concentration in down-gradient wells.

Site	Evidence of impact	Evidence of correlation[1]	Comment
EM1	No	Positive	-
EM2	No	Positive	-
EM3	Yes	Positive	-
EM4	Unknown	Unknown	Insufficient data
EM5	No	No	-
EM6	No	No	-
EM7	No	No	-
EM8	No	Unknown	Insufficient data
EM9	No	Negative	-
EM10	No	Positive	-
EM11	-	Positive	-
EM15	-	Positive	-
EM16	-	Positive	-

[1] Positive evidence of correlation includes positive correlations between sampling event and concentrations of chloride, sodium, potassium, ammonia, organic nitrogen or carbon, bacteria, and specific conductance and negative correlations between sampling event and concentrations of nitrate, sulfate, dissolved oxygen, and Eh.

Table 7: Summary of impact and correlation analysis at sites with permanent wells or tile lines.

In a third study, leachate collection systems (lysimeters) were installed beneath earthen-lined manure storage systems. Collection of flow data for the basin bottoms and sidewalls was sporadic, and we cannot estimate seepage through the basins during 1998 and 1999. Table 8 summarizes quality of seepage water at the three sites from 1998 through 2000.

Sample	Nitrate mg/L	Chloride mg/L	Potassium mg/L	Reduced nitrogen[1] mg/L	Sulfate mg/L
Dodge County					
Bottom	12.8	78	10	1.3	46
Center tile	33.7	48	2.5	0.06	255
Perimeter tile	26.8	63	12	56.8	67

Sidewall	20.2	58	109	1.7	122
Morrison County					
Bottom	0.70	131	31	1.8	49
Sidewall	1.05	569	18	5.4	87
Nicollet County					
Bottom	0.81	300	69	3.3	68
Sidewall	1.1	320	143	3.8	95
Perimeter tile	4.3	205	50	8.6	190

Sample	**Sodium**	**Organic carbon**	**Bicarbonate**	**Specific conductance**	**E. coli bacteria**
Dodge County					
Bottom	28	11	373	1225	1
Center tile	10	-	315	1440	-
Perimeter tile	22	-	410	1680	1-
Sidewall	119	34	310	1160	1
Morrison County					
Bottom	59	26	380	1724	-
Sidewall	83	87	495	3291	-
Nicollet County					
Bottom	175	43	-	2680	1
Sidewall	238	57	974	2995	-
Perimeter tile	93	-	717	2085	2

[1] Reduced nitrogen includes ammonia and organic nitrogen.

Table 8: Chemical concentrations in samples from lysimeter sites.

At the Dodge County site, concentrations of nitrate were greater in tile lines than in leachate from the cohesive soil-lined bottom and sidewall of the basin. This may reflect nitrate inputs from adjacent agricultural fields. Once tile line flows are calculated, we can conduct mass balance calculations to determine the flow contribution from the manure basin and from adjacent fields. The concentration of reduced nitrogen was greater in the perimeter tile compared to other samples. Ammonia was the primary contributor to the reduced nitrogen load, with a median concentration of about 51 mg/L. The source of the ammonia is unknown. Positive correlations between reduced nitrogen concentration and sampling event occurred in samples from the sidewall. This was the result of very high concentrations of reduced nitrogen in samples collected in 2000. Additional data is needed to determine if the correlation is due to differences in sampling or laboratory analysis.

At the Morrison County site, concentrations of most chemicals were greater in sidewall samples compared to samples collected through the bottom of the basin. Concentrations of reduced nitrogen in sidewall samples increased during the sampling period ($R^2 = 0.620$). Specific conductivity also increased during the sampling period ($R^2 = 0.773$), indicating increasing impacts to ground water from the manure basin. Concentrations of total nitrogen, however, remained below 7 mg/L. If all nitrogen was converted to nitrate, concentrations would still be below the drinking water standard of 10 mg/L.

At the Nicollet County site, concentrations of nitrogen were highest in samples from the perimeter tile. Concentrations of other chemicals, however, were lower in tile samples compared to bottom and sidewall samples. The data indicate leaching of mobile chemicals through the manure basin and subsequent dilution in tile lines. Adjacent agricultural fields contribute the diluting water, except for nitrogen, which is at higher concentration in leachate from the agricultural fields. Positive correlations were observed between concentrations of reduced nitrogen in bottom and sidewall samples and sampling event ($R^2 = 0.622$ and 0.838, respectively). Concentrations of total nitrogen, however, were less than 5.0 mg/L.

The data from the lysimeter studies, though incomplete, indicates leaching of chemicals through the manure basins. Leaching appears to be greatest through sidewalls. Maule (1995) observed similar results. Sidewalls are prone to drying and wetting as the level of liquid in the basin changes. This leads to cracking and increased flow rates during dry cycles. Rigorous analysis of the water quality data is needed, particularly with respect to rates of leaching through the basin bottoms and sidewalls.

Manure Storage Basins Constructed with Concrete Pits

In Minnesota, poured concrete-lined systems are most commonly used to store manure from swine. They are more expensive to install than earthen-lined systems. Concrete-lined systems are considered less permeable than earthen-lined systems, with a permeability of 10^{-8} cm/s or less. Concrete liners are not subject to problems with drying and cracking following clean-out of the manure, and there should be less leaching following clean-out compared to earthen systems. We conducted two studies involving concrete-lined basins.

In the first study, we examined water quality adjacent to manure basins older than five years. Table 9 illustrates maximum concentrations at each of the sites with concrete liners. Estimates of plume length are included in Table 9. Ground water impacts are limited to about 100 feet down-gradient of the manure basins. Even in down-gradient wells with elevated concentrations of chemicals compared to up-gradient wells, impacts from the manure basins are less than impacts from earthen liners, unlined basins, and open lots. Concentrations of phosphorus represent a potential concern for surface waters located within about 100 feet of the manure basins. Nitrate concentrations represent a potential drinking water concern immediately down-gradient of the manure basins, but even nitrate plumes did not extend more than about 100 feet from the basins.

		Maximum down-gradient concentration (mg/L)				
Site	**Approximate plume length (ft)**	**Ammonia**	**Total Kjeldahl nitrogen**	**Phosphorus**	**Total organic carbon**	**Potassium**
C1: basin 1	50	0.07	0.40	0.163	2.30	4.50
C1: basin 2	125	0.08	1.19	2.40	7.50	103
C2	100	2.32	21.2	14.4	142	179

Table 9: Approximate plume lengths and maximum concentrations of selected chemicals at the three sites with concrete-lined systems.

In the second study, we analyzed for correlations between chemical concentrations and sampling event at four sites where permanent monitoring networks were constructed at sites with new concrete-lined manure storage basins. The sites had no prior history of manure storage. No correlations were evident, but only three years of data had been collected at each site. Additional monitoring is required to analyze for trends.

Manure Storage Basins Constructed with Flexible Membrane Liners

A variety of synthetic materials are increasingly being used as liners in manure storage systems. These materials are often used in conjunction with earthen liners and include chlorosulfonated polyethylene (Hypalon); polyvinyl chloride (PVC); linear low density, medium density, and high density polyethylene; geocomposite clay lining; polypropylene; and woven polyester fabrics (Field Lining Systems, Inc.). Permeability of these materials are well below requirements for manure storage basins. These materials vary considerably in their performance and durability. Little information exists on the long-term effectiveness of these materials in protecting ground water quality.

We began monitoring a dairy farm where a new geosynthetic-lined manure basin was installed in 1997. The feedlot had been operated as an open lot for more than 40 years. Total nitrogen concentrations directly beneath the open feedlot decreased by about 55 percent since the manure storage system was installed (Figure 4). Reductions in ammonia concentrations account for most of the decrease in total nitrogen. Nitrate concentrations increased with time but remain below the drinking water standard of 10 mg/L. Concentrations of phosphorus and organic carbon also decreased since construction of the manure storage system (Figure 4), while concentrations of potassium, chloride, calcium, magnesium, sulfate, bicarbonate, and sodium have not changed.

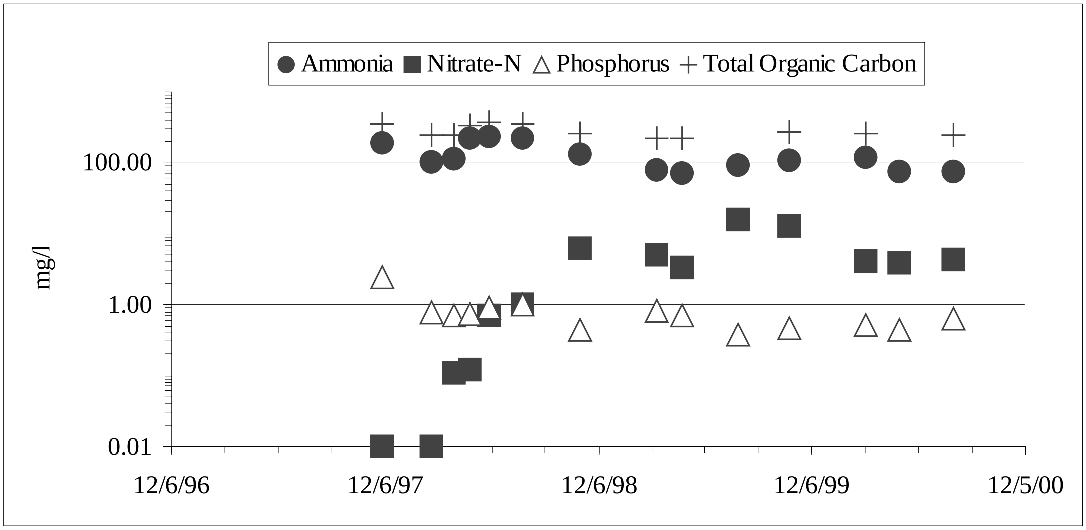

Figure 4: Concentrations of ammonia, nitrate, phosphorus, and organic carbon beneath the feedlot at the site with a geosynthetic liner.

No changes in water quality were evident in wells down-gradient of the storage system. We have not performed slug tests in the wells, but we estimate ground water velocity at 50 to 100 feet per year. The down-gradient wells are between 200 and 300 feet down-gradient of the feedlot. Water quality changes are not likely in these wells for another one to three years.

Comparison of All Sites

Because we employed the same sampling methods at each site with manure storage systems older than five years, we can compare water quality at the sites. Table 10 summarizes excess chemical concentrations at each site. Estimated plume length is included in Table 10. Except where noted in the table, plume length represents the distance from the center of the storage system to the furthest down-gradient well impacted by the manure storage system, or the distance from center of the system to a point halfway between impacted and non-impacted down-gradient wells. In cases where the ">" value is shown in Table 10, the plume would probably extend beyond the value given. At Site U1, for example, a plume intercepted a lake at about 320 feet. Concentrations of chemicals at the furthest down-gradient well were about as high as concentrations immediately down-gradient of the storage system at Site U1, suggesting that the plume was not attenuating or was attenuating very slowly.

Table 10 indicates chemical loading and plume length were greatest under unlined storage systems. Excess ammonia and Kjeldahl nitrogen were more than an order of magnitude greater under unlined systems than under any other storage system type. Plume length and excess concentrations of ammonia, chloride, and Kjeldahl nitrogen were least under concrete-lined systems. Excess phosphorus and organic carbon concentrations were relatively low at open lots. This may be due to adsorption of these chemicals in the vadose zone, since chemicals typically have further to leach compared to manure basins.

Site	**Ammonia**	**Chloride**	**Total Kjeldahl nitrogen**	**Total organic carbon**	**Potassium**	**Phosphorus**	**Plume length**
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	feet
Open lots							
O1	2.76	79.4	6.74	27.4	343	0.16	425
O2	0.58	29	0.12	-5.1	-	-	> 220
O3	28.4	572	36.3	-	318	0.42	400
O4	0.08	23.3	0.53	1.4	21.4	0.03	> 100
median	1.67	54.2	3.69	1.4	318	0.16	> 300

Unlined							
U1	265	257	374	71.7	179	1.05	> 320
U2	136	203	151	38.2	103	6.37	450
U3	163	81	187	22.1	-	3.01	> 125
median	163	203	187	38.2	141	3.01	> 320
Earthen-lined							
E1: basin 1	66.1	54.4	76.6	39	52	1.49	275
E1: basin 2	3.24	81.4	4.00	23	197	3.51	400
E2	0.03	52.7	0.26	1.9	-4.3	-0.09	325
E3	4.45	3.9	5.69	0.80	2.0	1.26	300
median	3.85	53.6	4.85	12.5	27	1.38	313
Concrete-lined							
C1: basin 1	0.04	-48.8	0.00	1.0	2.50	0.14	50
C1: basin 2	0.01	5.2	0.69	7.0	39.5	2.4	125
C2	-0.84	-13.4	15.0	136	141	6.9	100
Median	0.04	-13.4	0.69	7.0	39.5	2.4	100

Table 10: Excess chemical concentrations of chemicals in down-gradient wells at sites with manure storage systems older than five years.

To compare different types of systems, we used maximum concentrations and ranked sites from low to high concentration for chemicals indicated in Table 10. We then conducted Analysis of Variance on ranks. Table 11 indicates that unlined systems have the highest chemical concentrations and potentially the greatest impact on ground water.

Storage System	**Average rank**
Unlined	9.91 a
Earthen	6.08 b
Open lot	5.76 b
Concrete	4.25 b

Table 11: Comparison of average ranks between different liner systems. Different letters within a column indicate average ranks that differed significantly at the 0.05 level.

Table 12 summarizes concentrations of additional inorganic chemicals in wells located up-gradient and immediately down-gradient of manure storage systems. Concentrations of calcium, copper, and zinc did not differ between up-gradient and down-gradient wells and results for those chemicals are not included in Table 12. Although concentrations of chemicals were generally higher in down-gradient wells, concentrations were below drinking water standards.

Site	Location	Boron	Iron	Magnesium	Manganese	Sulfate
O1	Down-gradient	0.085	9.73	38.9	1.223	4.2
O1	Up-gradient	0.025	0.042	28.4	0.131	2.8
O2	Down-gradient	-	-	-	-	-
O2	Up-gradient	-	-	-	-	-
O3	Down-gradient	-	0.130	80.8	6.270	-
O3	Up-gradient	-	0.305	10.8	0.400	-
U1	Down-gradient	0.190	13.0	64.7	0.250	18.1
U1	Up-gradient	0.057	0.006	38.6	0.003	10.5
E1	Down-gradient	0.003	0.022	63.3	1.820	28.6
E1	Up-gradient	0.002	0.018	23.2	0.027	8.3
E2	Down-gradient	0.004	0.005	9.6	1.020	72.3
E2	Up-gradient	0.003	0.002	35.8	0.177	7.7
E3	Down-gradient	0.032	0.005	23.3	1.255	4.7
E3	Up-gradient	0.024	0.006	18.4	0.150	2.8
C2	Down-gradient	0.076	0.006	37.7	0.177	12.1
C2	Up-gradient	0.042	0.003	35.0	0.028	6.3

Table 12: Up-gradient and down-gradient concentrations of inorganic chemicals at several sites.

Summary and Future Work

Results from our studies indicate manure storage systems impact ground water. In our study using temporary wells at sites older than five years, we observed plumes down-gradient of all manure storage systems. Impacts were greatest at sites where manure was stored in basins lacking a constructed liner. Plumes extended several hundred feet at all sites except those with a concrete liner. Plumes at sites with concrete-lined systems were limited to distances of about 100 feet from the manure storage basin.

Plumes were typically characterized by high concentrations of ammonia, organic nitrogen, phosphorus, organic carbon, potassium, and chloride. Concentrations of ammonia and phosphorus represent potential concerns for surface water intersecting a plume. Ammonia and phosphorus attenuated within plumes, however, and were generally below levels of concern 200 feet down-gradient of the manure basin.

At two sites having earthen liners underlain by a thick unsaturated zone, plumes were characterized by high nitrate concentrations. Nitrate is slowly attenuated in ground water. A 200 foot setback distance from a well may not be protective for earthen-lined systems underlain by a thick, coarse-textured vadose zone.

Monitoring at an open feedlot where a new, geosynthetic liner was constructed showed improvements in water quality after just three years. Total nitrogen in ground water decreased by 55 percent over three years. Concentrations of phosphorus and organic carbon also decreased over the same period. The improvement in water quality is probably due to removal of manure-contaminated soil, reductions in animal activity on bare soil, and installation of a grass filter strip to capture runoff. Long term monitoring will be required to establish a relationship between water quality and the new liner system.

Monitoring at several sites with newly constructed earthen liners revealed variable results after five years of sampling. We observed positive correlations between sampling event and the concentration of one or more indicator at seven sites, while no correlation or a negative correlation was observed at six sites. Additional sampling is warranted at most of these sites to continue monitoring for trends in water quality.

These studies suggest additional work to better understand potential impacts from manure storage systems.

1. Conduct additional sampling for bacteria and viruses at sites that are likely to be impacted by manure management. Sampling in this study was restricted to bacteria. Sampling occurred primarily in down-gradient samples.
2. Conduct long-term monitoring at sites with concrete liners and geosynthetic liners. These represent systems that are most protective of ground water quality. Of particular interest are concrete or synthetic systems constructed at sites that previously had unlined systems or open lots.
3. Continue monitoring at sites with earthen-lined systems. The data used in this report are less than five years old. Sampling at older facilities showed ground water impacts from the earthen-lined systems. Long-term monitoring will help understand the time frames involved in plume development adjacent to these systems.
4. Expand sampling to include other chemicals of interest, including growth hormones, antibiotics, and steroids.
5. Conduct comparative risk analysis of unlined sites to determine if they represent a significant environmental risk compared to other land uses.

6. Continue sampling at the three sites with lysimeters and at sites with new concrete- or synthetic-lined systems.

One tool for positively identifying feedlot impacts in ground water would be use of labeled tracers, such as ^{13}C, ^{15}N, or ^{18}O. These can be expensive, however. Use of conservative tracers, such as chloride and bromide and some dyes, are other options.

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Appendix I – Reporting Limits And Laboratory Methods

Chemical	**Reporting Limit**	**Laboratory Method**
Inorganics		
Alkalinity	1 mg/L	Titration
Aluminum	0.049 mg/L	ICP
Ammonia	0.020 mg/L	Colorometric
Boron	0.13 mg/L	ICP
Cadmium	0.0019 mg/L	ICP
Calcium	0.055 mg/L	ICP
Chloride	0.10 mg/L	Ion Chromatography
Chromium	0.0034 mg/L	ICP
Copper	0.0055mg/L	ICP
Dissolved organic carbon	0.50 mg/L	Dohrman carbon analyzer
Dissolved oxygen	0.010 mg/L	Field meter
Eh	1 mV	Field meter
Fluoride	0.20 mg/L	Ion Chromatography
Iron	0.0034 mg/L	ICP
Lead	0.024 mg/L	ICP
Magnesium	0.020 mg/L	ICP
Manganese	0.00070 mg/L	ICP
Nickel	0.0061 mg/L	ICP
Nitrate	0.020 mg/L	Cadmium reduction
pH	0.1 pH unit	Field meter
Phosphorus	0.030 mg/L	ICP
Potassium	0.118 mg/L	ICP
Sodium	0.060 mg/L	ICP
Specific conductance	0.1 mmho/cm	Field meter
Sulfate	0.10 mg/L	Ion chromatography
Temperature	0.1 ^{o}C	Field meter
Total organic carbon	0.5 mg/L	Dohrman carbon analyzer
Total phosphorus	0.020 mg/L	ICP
Tritium (enriched)	0.8 tritium units	Liquid scintillation
Zinc	0.0027 mg/L	ICP