Effects of Liquid Manure Storage Systems on Ground Water Quality

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Foreword

This paper provides a comprehensive 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 thorough 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 is intended for technical audiences. A companion report provides an abbreviated version of the same information. A companion fact sheet provides a short, non-technical discussion of our work with feedlots. Although the report is for technical audiences, we do not discuss in detail results for each well sampled during the various studies.

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.

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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.

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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.
[2] Sites with unlined basins and some sites with compacted earthen basins do not meet current state requirements for manure storage.

We observed wide-ranging impacts at different sites. There was evidence of shallow ground water contamination down-gradient of manure storage areas at all sites. 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 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.

<u>Study 2</u>

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 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

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

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 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 one 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.

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

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 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.

1. 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 to lower the water table. Sampling at most of

[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.

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 one 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.

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

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

1.2. 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**
	Cattle	**Dairy**	**Dairy**	**Hog**	**Hog**	**Dairy**	**Hog**	**Hog**	
Chemical	mg/kg (dry weight basis)					mg/L			mg/L
Total phosphorus	79500	6188	6673	-	13350	-	-	-	0.056
Organic matter	283500	621000	-	-	-	-	-	-	2.4[1]
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 (Minn. R. ch. 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.

2. Field Investigation Methods, Materials, and Data Analysis Methods

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.

2.1. Temporary Well Investigations

We sampled several sites using direct push technology to install temporary wells. This method consists of installing a small diameter well, collecting a sample, and then sealing the well according to well sealing code. Most wells were screened within two feet of the water table. 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.

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-inch slot, four-foot temporary screen. We collected samples from the top two feet of the water table with a fully exposed screen. In deeper, nested wells, where a discrete sample was required, the screened interval was one to two 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 (Ca, Mg, Na, and K) and anions (NO_3^-, SO_4^{-2}, and Cl), ammonia-nitrogen, Kjeldahl-nitrogen, dissolved organic carbon, phosphorus, and fecal coliform bacteria[7]. 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

[7] Throughout the document, nitrate refers to NO_3-N, ammonia to NH_3-N, sulfate to SO_4-S, phosphate to PO_4-P, and phosphorus to total phosphorus as P.

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 Services Laboratory, Department of Soil, Water, and Climate, 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. Routine QA/QC criteria include:

- charge balances less than 10 percent;
- samples not exceeding recommended holding times;
- concentrations in primary and duplicate samples that do not vary by more than 10 percent;
- concentrations in field samples and laboratory duplicates that do not vary by more than 10 percent; and
- surrogate and spike sample recoveries that range from 80 to 120 percent.

All samples met QA/QC criteria. MPCA (1998c) summarizes field-sampling methods.

2.2. 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. 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.

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 X 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 $1x10^{-7}$ 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 ground water monitoring plans prior to sample collection. Perimeter tile lines and monitoring wells were installed and sampled two or more times prior to adding manure to the basins. Quarterly ground water sampling occurred following the addition of manure to the system. 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 sampling reports, as well as modifications to ground water monitoring plans.

At two sites, MPCA installed permanent monitoring networks. In 1997, an earthen manure storage basin with a 0.25-inch geosynthetic, bentonite clay liner was installed at a site in Isanti County. The liner was covered with one 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, *E. coli* bacteria, Kjeldahl nitrogen, ammonia, and trace inorganic chemicals. MPCA (1998a) describes well construction methods.

2.3. Sites with 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 two to three weeks during the first five months of operation and was sampled approximately nine 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.

2.4. 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 (Helsel and Hirsch, 1993). 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 concentration 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 and organic carbon in down-gradient wells with concentrations in up-gradient wells. If down-gradient concentrations of these two 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 a plume extended halfway between the two wells. Because these sites were typically more than ten years old, we assumed plumes at most sites were stable.

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 tested differences in concentration between up- and down-gradient wells for normality. 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 tested for correlation between sampling event and chemical concentration 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.

3. Open Feedlots

3.1. Abstract

We sampled ground water adjacent to four open feedlots that were more than five years old. Plumes were evident at each site and extended for distances of more than 400 feet at two of the sites. High concentrations of reduced nitrogen, organic carbon, and chloride characterized plumes at these two sites. Concentrations of ammonia and phosphorus represent potential concerns for surface water intersecting these plumes. At the two remaining sites, which had thick unsaturated zones underlying the manure storage system, oxidizing conditions occurred beneath the feedlots and nitrate contamination of ground water was evident down-gradient of the feedlots. Plume lengths could not be accurately estimated at these sites because of limited sampling, but we identified ground water impacts at least 100 feet down-gradient of the open lots. Nitrate concentrations exceeded drinking water criteria down-gradient of the feedlot at one site.

3.2. Introduction

Most open lots in Minnesota consist of small areas, less than five acres, where animals are confined. The upper 6 inches of soil are compacted in these high traffic areas. Mielke et al. (1969) found ammonia concentrations of 440 mg/kg[8] and total nitrogen concentrations of 7600 mg/kg at the soil surface beneath a beef cattle feedlot. Concentrations decreased rapidly in the

[8] All weights in this report are on a dry weight basis, unless otherwise stated.

upper six inches of soil and were less than 10 mg/kg at 35 inches. Nitrate was not detectable in the upper 20 inches of soil because of the high biochemical oxygen demand of manure, which leads to nitrate-reducing conditions. Elliott and McCalla (1972) observed soil gas concentrations of 8 to 52 percent methane, 12 to 23 percent carbon dioxide, and less than one percent oxygen in soil beneath an open feedlot. These conditions preclude the presence of nitrogen in an oxidized form. Schuman and McCalla (1975) observed potassium saturation in the upper 15 cm beneath an open lot having beef cattle. Calcium was the dominant cation below this depth, indicating ion exchange of potassium for calcium in the upper soil profile.

Soils at an open feedlot are subject to cracking, shrinking, or swelling due to seasonal weather patterns. With no protective layer below the soil surface, water seeping through the upper six inches of soil travels quickly to ground water. Water leaching through the soil and vadose zone and into ground water contains reduced carbon and reduced nitrogen. Gillham and Webber (1969) observed elevated ammonia concentrations in ground water up to 600 feet down-gradient of an open lot containing 65 head of beef cattle. Ground water impacts tend to be greatest in upland areas where slopes are less than 5 percent, probably because there is less overland runoff and high soil infiltration rates (Ellis et al., 1975). Lorimor et al. (1972) observed low nitrate concentrations down-gradient of an open feedlot in Nebraska. They did not sample for other nitrogen chemicals, however.

3.3. Monitoring in Minnesota

MPCA ground water monitoring at open feedlots consisted of sampling at older, established feedlots. We selected four open lots for sampling. The primary areas of concern were unroofed areas where animal activity occurred on bare soil. All sites were located on coarse-textured soils. These conditions represent a hydrogeologic setting in which chemicals from manure have the greatest potential to leach to ground water. Table 2 summarizes characteristics of these sites. Figure 1 illustrates the location of the sites.

Site	Animal	Animal units	Approx. Years of operation	Soil	Approximate depth to water (ft)[1]
O1	Beef	700	20	Coarse sand and gravel	7 to 15
O2	Beef	300	20	Coarse sand	15 to 20
O3	Dairy	100	40	Loamy sand	10 to 15
O4	Hog	50	More than 20	Coarse sand	12

[1] These depths represent the range of depths encountered during drilling of temporary wells.

Table 2: Open lots sampled.

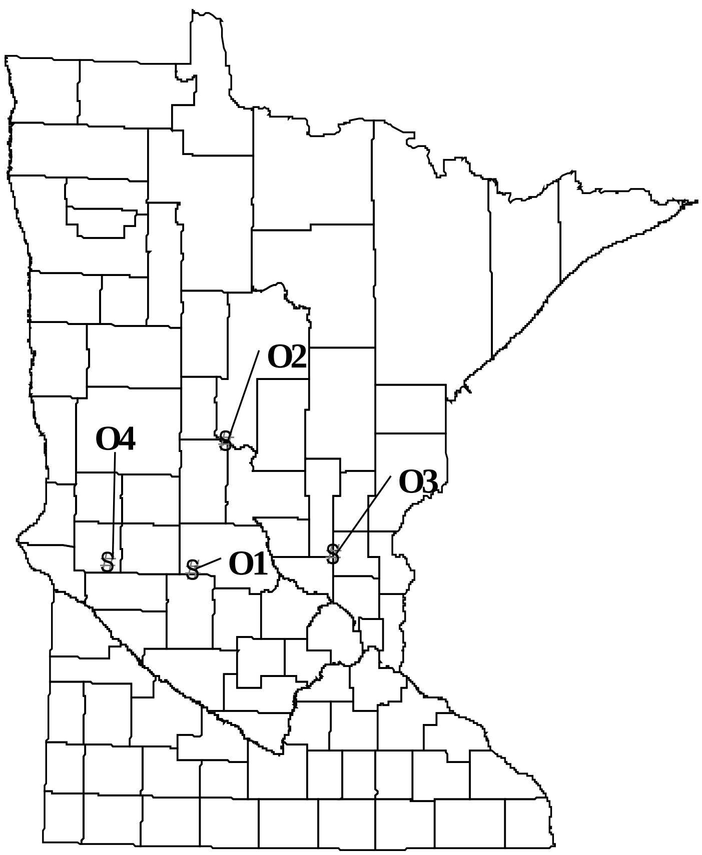

Figure 1: Location of sites with open lots.

3.3.1. Site O1

Figure 2 illustrates the location of temporary wells at Site O1. Ground water flow is to the north-northeast. Table 3 summarizes water quality data for each of the wells.

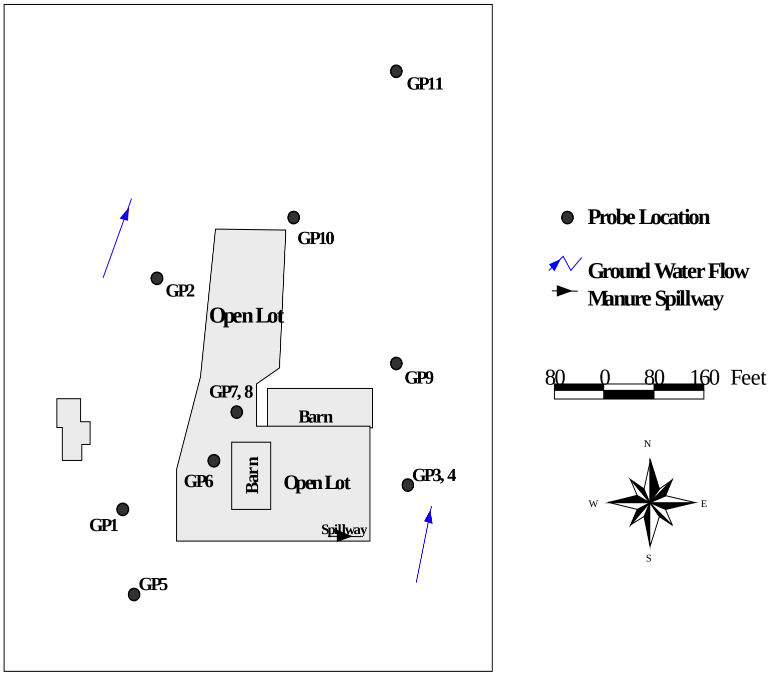

Figure 2: Location of temporary wells and direction of ground water flow at Site O1.

Wells 1 and 5 were hydraulically up-gradient of the feedlot and had low ranks (4.3 and 4.8, respectively), while wells 2 and 10 had high ranks (8.8 and 8.3, respectively)(see Section 2.4 for a description of the ranking procedure). Well 2, is located in a depression adjacent to the feedlot. Manure runs off from the feedlot into this depression. Water quality in Well 2 is impacted by leaching from this manure, with high concentrations of chloride, organic carbon, ammonia, potassium, and Kjeldahl nitrogen.

Well 10 was impacted by the feedlot, with concentrations of Kjeldahl nitrogen, ammonia, and organic carbon more than ten times greater than concentrations in up-gradient wells. Nitrate-reducing conditions occurred in this well, and nitrate was below the reporting limit of 0.020 mg/L. Well 11 had chloride and organic carbon concentrations that were more than double the concentrations in up-gradient wells, but the overall rank of 5.1 was low. We estimated a plume length of approximately 425 feet from the center of the feedlot to Well 11 (see Section 2.4 for a description of methods used in estimating plume length).

Concentrations of *Escherechia coli* bacteria were highest in Well 6, directly under the feedlot. *E. coli* bacteria were present in Well 10, but at lower concentrations than in Well 6. Ammonia concentrations were highest in Wells 10 (3.88 mg/L) and 2 (2.84 mg/L).

Well location	Well ID[1]	Ammonia	Chloride	Dissolved organic carbon	Eh	Iron	Nitrate	Potassium
		mg/L	mg/L	mg/L	MV	mg/L	mg/L	mg/L
Up	1	0.050	10.6	1.20	313	0.0050	13.6	1.51
Up	5	0.120	13.4	1.50	286	0.079	32.7	5.73
Side	2	2.84	91.9	28.9	244	14.9	1.99	94.9
Side	3	0.260	111	14.3	263	0.231	66.2	348
Side	4	0.120	30.1	3.80	267	0.018	50.9	6.98
Feedlot	6	0.060	92.8	3.40	262	0.019	26.8	13.2
Feedlot	7	0.190	53.0	3.20	256	0.099	5.61	6.73
Feedlot	8	0.060	2140	2.60	269	0.013	29.1	4.02
Down	9	1.06	7.03	7.20	149	0.072	30.5	69.2
Down	10	3.88	92.0	26.1	284	4.60	< 0.020	95.5
Down	11	0.100	38.1	3.60	296	0.023	18.9	34.5
Well location	**Well ID**	**Sodium**	**Specific conductance**	**Sulfate-S**	**Total Kjeldahl nitrogen**	**Phosphorus**	**E. Coli**	**Average rank**
		mg/L	Umohs/cm	mg/L	Mg/L	mg/L	MPN/100ml	
Up	1	3.75	1229	1.92	0.320	< 0.020	-	4.3
Up	5	6.74	1269	3.77	0.530	0.028	-	4.8
Side	2	45.2	1988	5.93	7.070	0.191	-	8.8
Side	3	17.5	1031	17.1	2.410	0.025	0	5.9
Side	4	9.23	950	6.79	0.600	< 0.020	-	5.2
Feedlot	6	16.7	1182	7.22	0.610	< 0.020	170	5.3
Feedlot	7	15.8	927	4.91	0.790	< 0.020	0	6.4
Feedlot	8	9.62	1204	4.77	0.560	< 0.020	-	5.5
Down	9	10.9	1382	10.0	2.420	< 0.020	-	6.0
Down	10	28.9	990	2.48	7.270	0.086	2	8.3
Down	11	16.8	839	6.88	0.890	0.034	-	5.1

[1] Wells were screened within two feet of the water table, except Wells 4 and 8, which were screened 7 feet below the water table.

Table 3: Summary of water quality at Site O1. Well locations are hydraulically relative to the animal containment area, where Up = up-gradient, Side = side-gradient, Down = down-gradient, and Feedlot = in the containment area.

Well 8 was nested with Well 7 and screened about four feet deeper than well 7. Chloride concentrations were high in Well 8 (2140 mg/L). Concentrations of other chemicals were similar to Well 7. The chloride concentration in Well 8 appears to be an anomaly, because of the similarities with concentrations of other chemicals.

3.3.2 Site O2

Figure 3 illustrates the location of temporary wells at Site O2. Ground water flow is to the northeast. Table 4 summarizes water quality data for each of the wells.

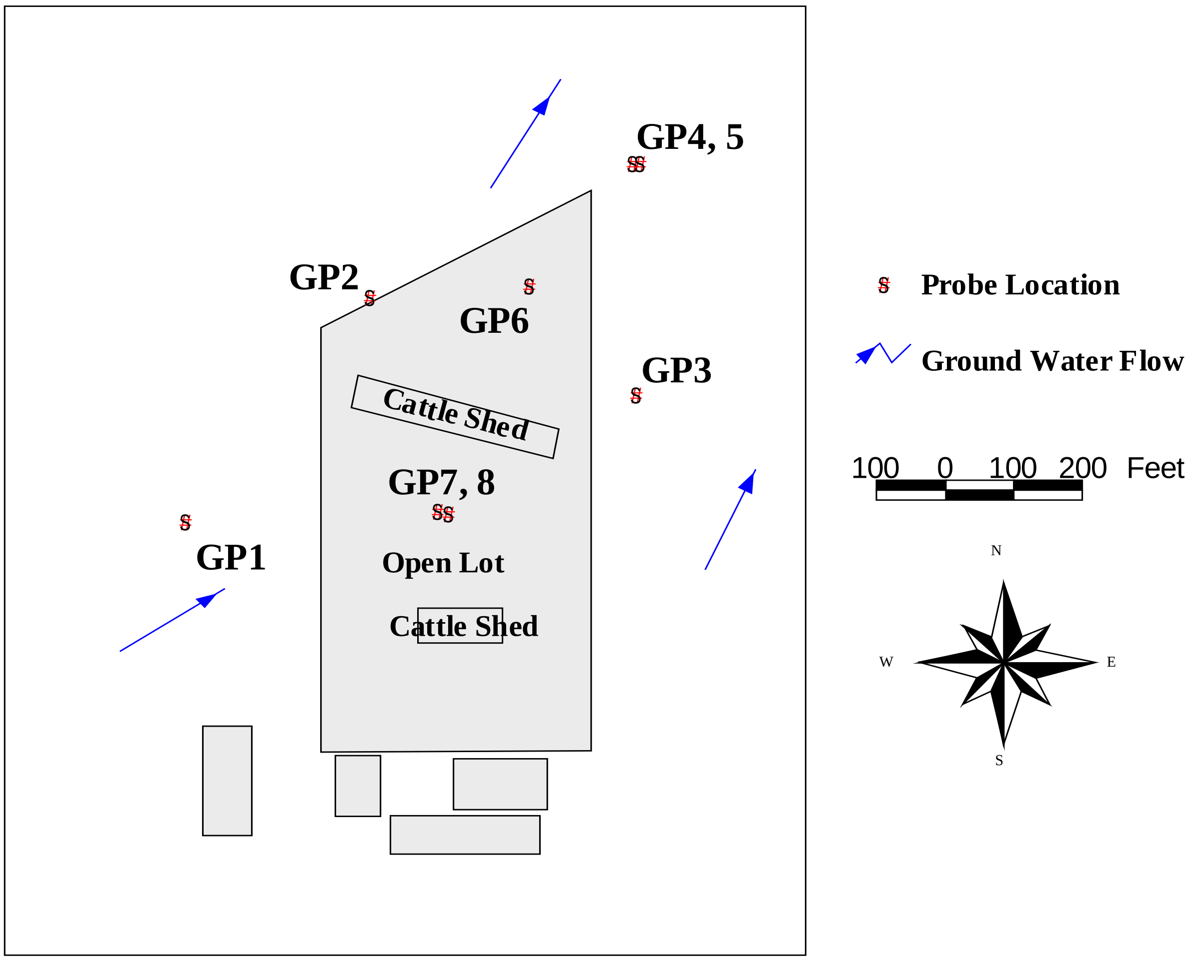

Figure 3: Location of temporary wells and direction of ground water flow at Site O2.

Ground water impacts from the feedlot at Site O2 were not as evident as at Site O1. The up-gradient well (Well 1) had high concentrations of organic carbon and organic nitrogen compared to Well 4, located down-gradient of the feedlot. Concentrations of dissolved oxygen were lower in up-gradient wells than in down-gradient wells. Nitrate concentrations were an order of magnitude or more greater in down-gradient wells. Two factors may account for the observations at Site O2. First, depth to water was more than 15 feet, which is thicker than that found at most other sites. Second, Site O2 operates as a temporary feedlot, where animals are removed on a periodic basis and manure and soil are scraped and removed. Because of the intermittent animal activity and the deep water table, soils at the site may not be excessively compacted and water leaching through the soil may be oxidized. Nitrogen therefore leaches as nitrate. Total nitrogen concentrations at Wells 4 and 5, located about 220 feet down-gradient of the feedlot, were about an order of magnitude greater than in Well 1. A nitrate plume therefore extends at least 220 feet from the feedlot.

Well location	Well ID	Ammonia	Chloride	Dissolved organic carbon	Dissolved oxygen	Eh	Nitrate
		mg/L	mg/L	mg/L	mg/L	mV	mg/L
Up	1	0.430	120	13.7	0.91	282	2.28
Side	2	0.220	282	8.60	1.43	329	45.8
Feedlot	8	0.090	122	6.90	3.12	294	21.0
Feedlot	7	0.180	149	5.00	1.30	210	7.15
Feedlot	6	0.130	113	3.90	1.25	319	40.9
Down	5	1.01	81.6	2.00	7.45	341	22.6
Down	4	0.100	145	3.70	7.64	371	70.1
Down	3	0.070	84.7		7.38	377	34.4

Well location	Well ID	Specific conductance	Sulfate-S	Total Kjeldahl nitrogen	E. Coli	Average Rank
		umhos/cm	mg/L	mg/L	MPN/100ml	
Up	1	1043	15.4	2.01	-	2.0
Side	2	1828	21.8	1.36	0	3.7
Feedlot	6	1099	16.4	0.88	0	4.7
Feedlot	7	1080	31.6	0.94	-	2.7
Feedlot	8	1134	12.3	1.04	1	4.2
Down	3	984	10.6	0.58	0	6.8
Down	4	1360	15.4	0.52	-	6.3
Down	5	955	16.9	2.13	-	5.7

[1] Wells were screened within two feet of the water table, except Wells 5 and 8, which were screened 7 feet below the water table.

Table 4: Summary of water quality at Site O2. Well locations are hydraulically relative to the animal containment area, where Up = up-gradient, Side = side-gradient, Down = down-gradient, and Feedlot = in the containment area.

Wells 4 and 5 formed a nest, with Well 5 screened about three feet below Well 4. Well 5 had higher concentrations of ammonia and Kjeldahl nitrogen and lower concentrations of nitrate than Well 4, but it also had lower concentrations of chloride and potassium than Well 4. The plume appears to extend three or more feet vertically into the aquifer down-gradient of the manure basin.

3.3.3. Site O3

Figure 4 illustrates the location of temporary wells at Site O3. Ground water flow is to the southeast. Table 5 summarizes water quality data for each of the wells.

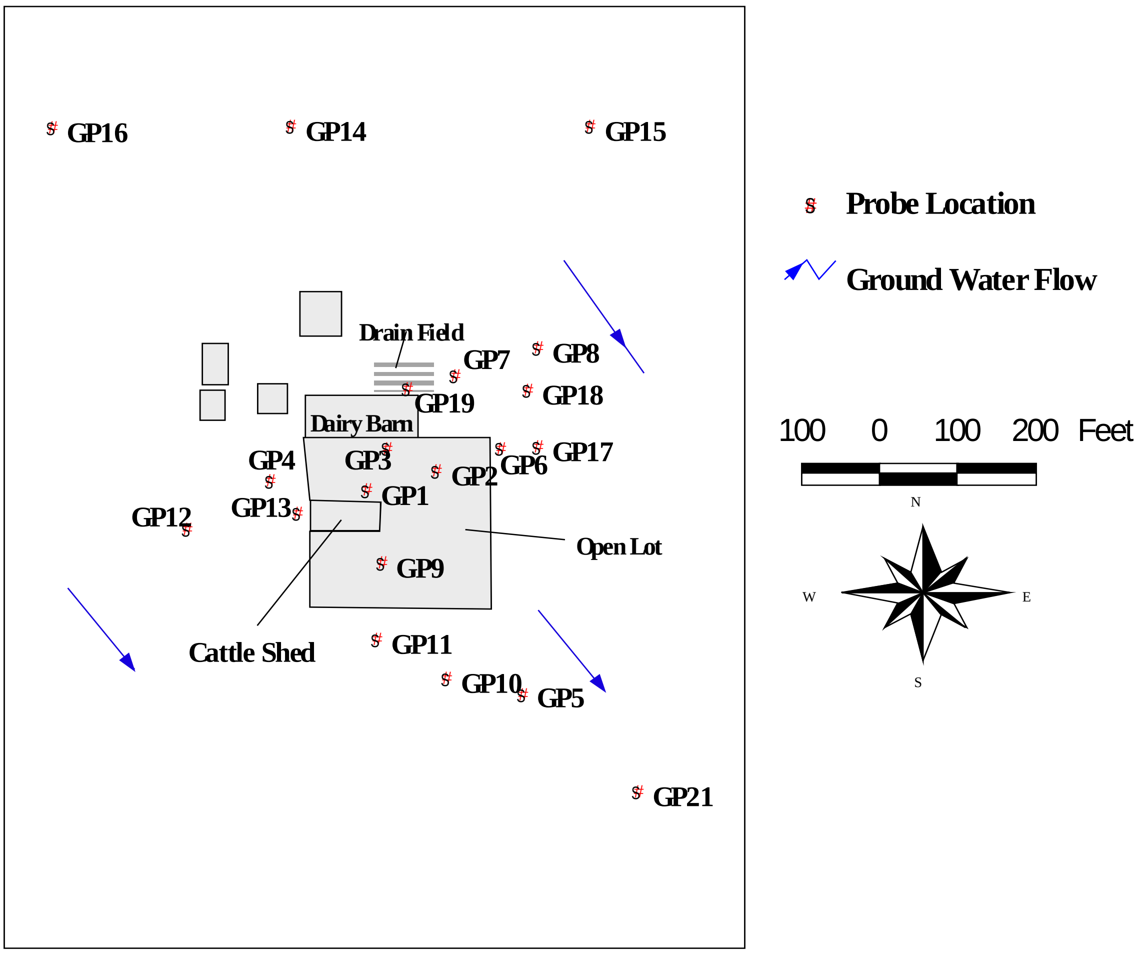

Figure 4: Location of temporary wells and direction of ground water flow at Site O3.

Well location	Well ID	Ammonia	Chloride	Eh	Iron	Nitrate	Phosphorus
		Mg/L	mg/L	mV	mg/L	mg/L	mg/L
Up	12	0.090	5.30	255	0.360	3.90	0.060
Up	13	0.765	152	48	2.72	89.3	0.260
Up	14	0.130	51.4	143	0.500	36.5	0.110
Up	4	7.49	205	-43	1.10	35.7	0.470
Side	6	0.110	76.5	214	0.290	26.9	0.230
Side	7	0.205	102	287	0.250	75.0	0.140
Side	8	0.160	91.0	206	0.620	34.3	0.160
Side	15	0.070	37.2	100	0.030	15.8	0.140
Side	18	0.240	334	362	1.16	84.4	0.220
Side	19	0.550	12.3	174	1.25	59.7	0.100
Feedlot	1	23.2	592	-229	5.76	0.250	0.890
Feedlot	3	35.9	179	-32	4.11	23.8	0.200
Feedlot	9	12.5	724	85	2.15	14.8	0.600
Feedlot	2	2.14	392	-	3.60	19.1	0.580
Down	11	0.250	20.7	235	0.560	32.8	0.080
Down	5	0.270	96.7	168	0.560	30.6	0.080
Down	21	0.070	71.6	198	0.198	36.2	0.13
Down	10	0.150	14.4	295	0.250	57.6	0.050
Well location	**Well ID**	**Potassium**	**Sodium**	**Specific conductance**	**Total Kjeldahl nitrogen**	**E. coli**	**Average Rank**
		mg/L	**mg/L**	**umhos/cm**	**mg/L**	**MPN/100ml**	
Up	12	2.70	3.30	127	< 0.100	-	6.4
Up	13	354	31.6	2245	1.19	-	12.8
Up	14	2.70	9.00	913	0.310	-	7.9
Up	4	31.5	59.4	1820	8.61	-	15.1
Side	6	4.80	19.4	931	0.450	0	10.1
Side	7	1.90	30.2	1215	0.990	0	8.5
Side	8	1.30	6.80	1094	< 0.100	0	8.3
Side	15	2.40	8.10	535	0.330	-	9.6
Side	18	2.40	23.8	1985	0.610	-	8.6
Side	19	7.30	7.20	798	0.570	-	7.6
Feedlot	1	673	196	-	44.9	-	15.6
Feedlot	3	369	30.5	2329	41.4	-	14.3
Feedlot	9	134	197	3681	22.7	-	16.4
Feedlot	2	385	52.2	-	5.93	-	11.4
Down	11	3.40	14.4	466	0.555	-	9.3
Down	21	1.3	8.3	579	0.25	-	7.6
Down	5	25.9	23.6	800	< 0.100	-	11.6
Down	10	5.40	10.4	645	< 0.100	0	6.6

Table 5: Summary of water quality at Site O3. Well locations are hydraulically relative to the animal containment area, where Up = up-gradient, Side = side-gradient, Down = down-gradient, and Feedlot = in the containment area.

Wells 1, 3, and 9, located in or just down-gradient of the feedlot, are impacted by the feedlot. Average ranks in these wells exceeded 14, compared to 6.4 in Well 12. We observed ammonia concentrations as high as 35.9 mg/L and total nitrogen concentrations as high as 41.4 mg/L down-gradient of the feedlot. Concentrations of nitrate in up-gradient wells were more than 35 mg/L, except for Well 12. Well 12 is located in an area where crops are not grown, and it appears to be less affected by agricultural activities than Wells 4, 13, and 14. Concentrations of phosphorus, chloride, and iron were much higher beneath and just down-gradient of the feedlot compared to other locations. A plume appears to extend to Well 5, as indicated by elevated concentration of chloride compared to up-gradient wells. The average rank in Well 5 was 8.6. The average rank in Well 21, located about 600 feet down-gradient of the feedlot, was 4.6. A plume, therefore, extends somewhere between Well 5 and Well 21. We estimated a distance of 400 feet.

3.3.4. Site O4

Figure 5 illustrates the location of temporary wells at Site O4. Ground water flow is to the southeast. Table 6 summarizes water quality data for each of the wells.

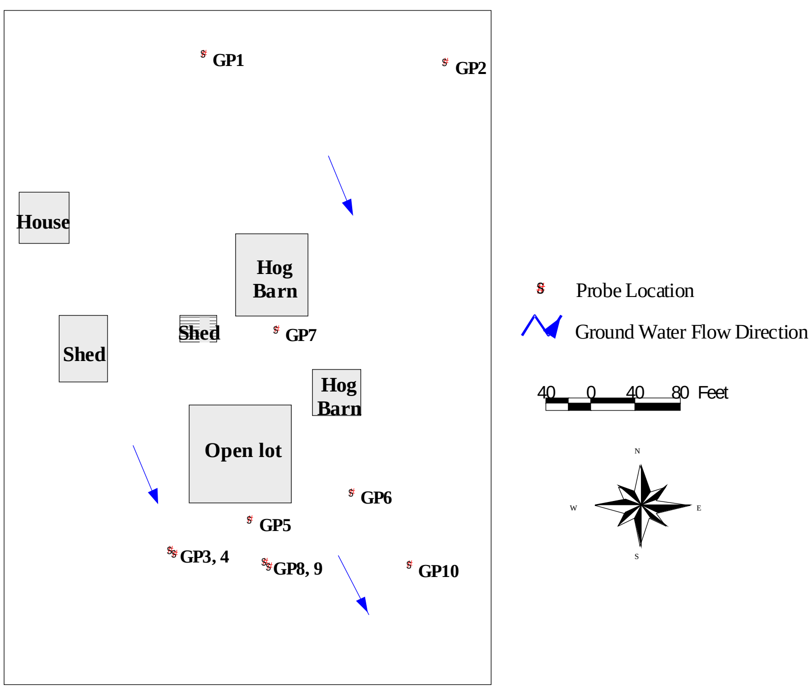

Figure 5: Location of temporary wells and direction of ground water flow at Site O4.

Locale	Well ID	Ammonia mg/L	Chloride mg/L	Eh mV	Iron mg/L	Manganese mg/L	Nitrate mg/L
Up	1	0.02	1.84	230	0.0158	0.0086	0.45
Up	2	0.02	4.32	230	0.0073	0.043	0.74
Down	3	0.03	15.4	234	0.0117	0.0046	0.5
Down	4	0.10	22.5	211	1.44	0.46	<0.020
Down	5	0.03	21.3	230	0.0364	0.62	11.9
Down	7	0.03	2.99	234	0.0122	0.018	6.22
Down	8	0.03	27.6	240	0.0276	0.18	12.3
Down	9	0.10	26.5	142	1.49	0.49	<0.020
Down	10	0.04	11.9	195	0.0157	0.37	8.31

Locale	Well ID	Phosphorus mg/L	Sodium mg/L	Specific conductance Umhos/cm	Sulfate mg/L	E. coli MPN/100-ml	Average Rank
Up	1	<0.016	4.38	483	1.74	< 1	3.3
Up	2	0.0252	4.80	520	4.67	< 1	3.3
Down	3	<0.016	12.1	610	11.6	< 1	3.4
Down	4	0.0568	5.20	760	27.2	-	6.3
Down	5	0.0298	23.8	843	13.0	< 1	5.3
Down	7	0.0400	8.17	603	4.83	< 1	3.8
Down	8	0.0168	25.1	830	15.1	< 1	4.2
Down	9	0.0554	5.58	730	43.3	-	6.4
Down	10	0.0276	10.2	823	16.2	< 1	-

[1] Wells were screened within two feet of the water table, except Wells 4 and 9, which were screened 7 feet below the water table.

Table 6: Summary of water quality at Site O4. Well locations are hydraulically relative to the animal containment area, where Up = up-gradient, Side = side-gradient, Down = down-gradient, and Feedlot = in the containment area.

Wells 5, 8, and 10, located down-gradient of the open lot, show impacts from the open lot. Specific conductance and concentrations of sodium were higher in these wells than in up-gradient wells (Wells 1 and 2), while total nitrogen concentrations were more than an order of magnitude greater than in up-gradient wells. Nearly all the nitrogen occurred as nitrate. Depth to water was only about 12 feet at Site O4, but there appears to be a mechanism for nitrate to reach and persist in ground water. Using the elevated nitrate concentrations in Wells 5 and 8 as an indicator of feedlot impacts, we estimate plume length to be at least 100 feet. Well 9, which was nested with Well 8 and was screened five feet below the water table, showed elevated chloride concentrations compared to up-gradient wells. Nitrate concentrations in Well 9 were low, however, because of nitrate-reducing conditions. It is unclear if the nitrate-reducing conditions were associated with seepage through the open lot, or if ground water naturally becomes more reducing with depth. We have observed rapid changes in Eh with depth in shallow sand aquifers (MPCA, 1998a).

3.4. Summary

Table 7 shows excess concentrations of ammonia, Kjeldahl nitrogen, phosphorus, total organic carbon, and potassium down-gradient of the manure storage areas at open feedlot sites. Excess concentration is the difference between down-gradient and up-gradient concentration. Excess concentration provides an indication of ground water chemical loading from the feedlot. Estimates of plume length are included in Table 7. Plumes at sites O1 and O3 extended for distances of more than 400 feet and were nitrate-reducing over most of their length. To illustrate the distribution of chemicals in a ground water plume at a feedlot, we plotted concentrations of ammonia, dissolved oxygen, total nitrogen, and phosphorus along a transect from Site O3 (Figure 6). A log scale is used in Figure 6 because concentrations of some chemicals vary up to three orders of magnitude as ground water passes beneath and then down-gradient of the manure storage system. Plumes at Sites O1 and O3 were characterized by high concentrations of ammonia, organic nitrogen, and organic carbon, occasionally high concentrations of phosphorus, and chloride, 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. Soils were coarser at these two sites compared to Sites O1 and O3, and the depth to water was more than 12 feet at Sites O2 and O4. The results suggest that ammonia is oxidized to nitrate in the unsaturated zone. Nitrate-enriched plumes extended at least 100 feet and probably much more at Sites O2 and O4, considering the mobility of nitrate. Nitrate concentrations represent a potential concern for drinking water receptors down-gradient of the feedlot at Site O2.

Site	Approximate plume length (ft)	Excess down-gradient concentration (mg/L)					
		Ammonia	Nitrate	Total Kjeldahl nitrogen	Phosphorus	Organic carbon	Potassium
O1	425	2.76	-2.2	6.74	0.16	27.4	-2.2
O2	More than 220	0.58	67.8	0.12	-	-5.1	67.8
O3	400	28.4	-31.7	36.3	0.42	-	-31.7
O4	More than 100	0.08	11.6	0.53	0.03	1.4	11.6

Table 7: Approximate plume lengths and excess chemical concentrations at open lot sites.

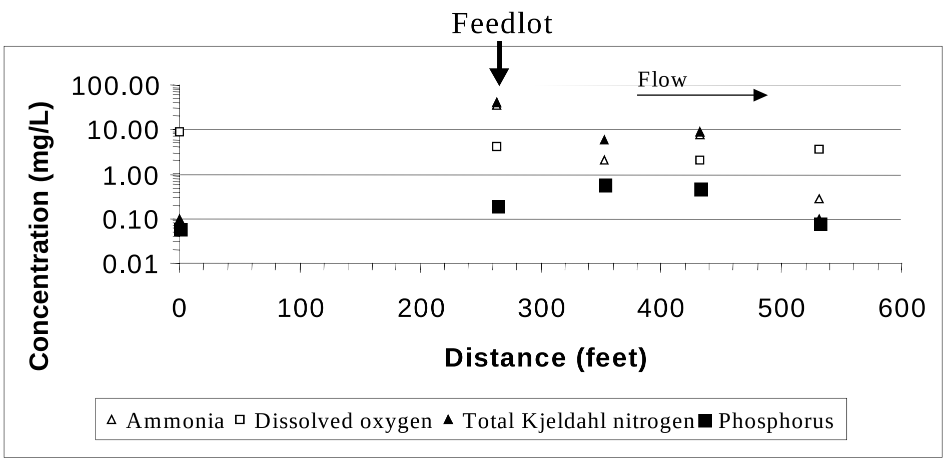

Figure 6: Distribution of chemicals along a ground water flow path passing beneath the open feedlot at Site O3. Concentrations are in mg/L.

4. Manure Storage Basins Constructed without a Soil Liner

4.1. Abstract

We sampled three sites having manure storage basins with no constructed liner (unlined basins). Each of the sites was older than five years. Wells immediately down-gradient of unlined basins were impacted by the basin. Maximum concentrations of ammonia and organic nitrogen immediately down-gradient of the basins typically exceeded 100 mg/L, while phosphorus concentrations exceeded 5 mg/L. These concentrations represent concerns for surface water if plumes intersect lakes or rivers. Both ammonia and phosphorus were attenuated within plumes, and the distribution of these chemicals in ground water down-gradient of the unlined basins varied between sites.

4.2. Introduction

Earthen manure storage basins constructed without a permit often did not have a constructed liner. These basins may have simply been excavated holes in the ground or natural depression areas where manure was stored.

Like all systems for storing manure, an organic seal forms at the manure-soil interface at the bottom of an unlined basin. The amount of leaching to ground water is greater than for a permitted lined system (Maule, 1995). First, there may be rapid infiltration of wastewater prior to seal formation. Second, rapid infiltration may continue through sidewalls and the bottom of the basin if preferential flow pathways exist. Third, waste may directly enter ground water if the seasonal high water table rises above the base of the manure. Fourth, the seal only slows, rather than prevents, infiltration.

Studies of unlined basins show considerable variability in impacts to ground water. Westerman et al. (1993) studied two unlined swine waste basins in a sandy, coastal plain soil. At both sites, significant impacts were observed in down-gradient wells. At one site, concentrations of ammonia exceeded 1 mg/L and chloride concentrations were close to concentrations measured in swine effluent. At the second site, ammonia concentrations were as high as 50 mg/L in down-gradient wells and chloride concentrations were about half the concentration measured in swine effluent. Concentrations in down-gradient wells did not change after about 3.5 to 5 years, indicating continued seepage through the basins and incomplete formation of a seal at the base of the basin. Miller et al. (1976) observed buildup of ammonium and phosphorus in soils beneath four unlined hog basins. The depth of chemical penetration ranged from 8 to more than 60 inches. Although they did not collect samples from ground water, they speculated that, at sites where penetration of chemicals is deep, significant degradation of ground water occurs.

Ritter et al. (1984) observed significant increases in nitrate concentrations down-gradient of a two-stage, unlined hog basin built in sandy soils. Concentrations of other chemicals were not elevated in down-gradient wells. The basin appeared to be effective at filtering out organic waste, phosphorus, and pathogens, while nitrogen passed through the bottom of the basin. This pattern of leaching is similar to that observed in septic systems, where ammonia passes through the organic biomat and is converted to nitrate in the vadose zone (Wilhelm et al., 1994; Harman et al., 1996).

Korom and Jeppson (1994) studied soil water quality beneath two unlined dairy basins on coarse-textured soils. They observed nitrate concentrations of 10 to 38 mg/L, with the lowest concentrations just prior to clean-out of the basins. Nitrate concentrations increased rapidly following clean-out, with concentrations up to 200 mg/L. The seepage rates through these basins were nearly an inch per day, which is considerably greater than rates typical of lined basins (about 0.01 to 0.05 inch per day). Huffman and Westerman (1995) observed low rates of nitrogen loss from five unlined swine basins, while high rates were observed at two sites. The primary factor affecting the rate of nitrogen loss appeared to be hydraulic conductivity of the soil underlying the basins. Leaching losses of ammonia, phosphorus, and nitrogen were low at two unlined sites located in Minnesota (Barr Engineering, 1982). These sites were located in alluvial soils and included a dairy operation and a hog operation.

4.3. Monitoring in Minnesota

We used temporary wells to sample ground water at three sites having unlined storage systems that were more than five years old. Table 8 summarizes characteristics of these sites. Figure 7 illustrates the location of these sites. Each site was located on coarse-textured soil and represents conditions where ground water is vulnerable to contamination.

Site	Animal	Animal units	Years of operation	Approx. depth to water (ft)[1]	Soil
U1	Hog	250	25	15 to 25	Coarse sand and gravel
U2	Hog	250	13	2 to 6	Coarse sand
U3	Hog	50	More than 20	12	Coarse sand

[1] These depths represent the range of depths encountered during drilling of temporary wells.

Table 8: Sampling sites with unlined manure storage systems.

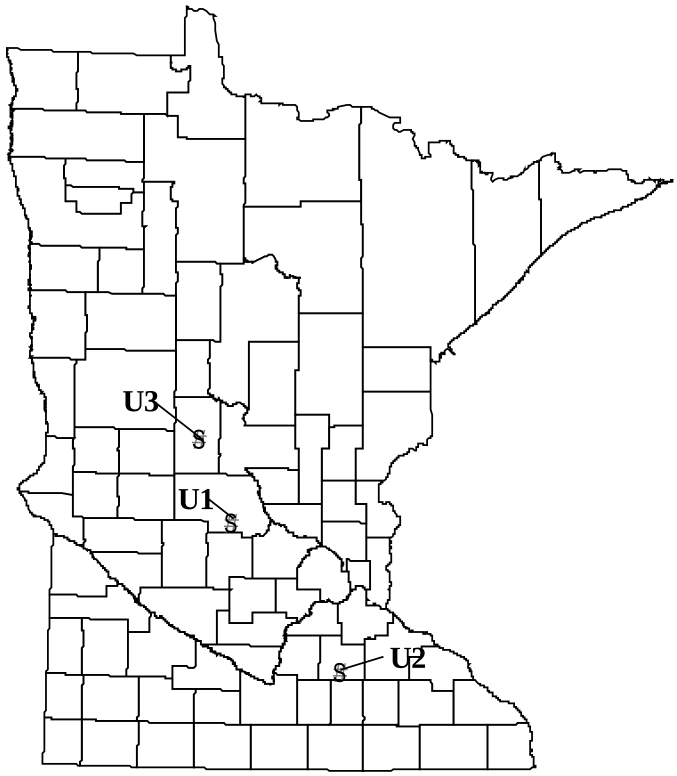

Figure 7: Location of sites with unlined manure storage systems.

4.3.1. Site U1

Figure 8 illustrates the location of temporary wells at Site U1. Ground water flow is to the southeast. Table 9 summarizes water quality data for each of the wells.

Well 3, located up-gradient of the feedlot, had low concentrations of ammonia (0.050 mg/L), Kjeldahl nitrogen (0.200 mg/L), phosphorus (0.046 mg/L), and total organic carbon (2.80 mg/L) compared to most other wells. Ambient ground water at this site appeared to have nitrate concentrations in excess of 45 mg/L, presumably due to adjacent agricultural production. Impacts from the manure basin were less evident in Well 1 than in Wells 6, 9, and 13, although Well 1 was the down-gradient well closest to the manure basin. During sampling, Well 1 only penetrated about eight inches into the aquifer and may not represent water quality immediately down-gradient of the basin. Wells 6, 9, and 13, also located down-gradient of the feedlot, are impacted by the manure basin. Concentrations of ammonia, Kjeldahl nitrogen, phosphorus, and total organic carbon exceeded 150, 153, 0.360, and 16.0 mg/L, respectively, in each of these wells. Nitrate-reducing conditions were observed in these wells, with Eh values of less than 180 mV, dissolved oxygen concentrations less than 1.1 mg/L, and nitrate concentrations less than 0.020 mg/L. A plume extended from the manure basin to the adjacent lake. This is a distance of about 320 feet along the ground water flow path. We assume the plume would extend much farther if the lake were not present, since concentrations of ammonia, total nitrogen, phosphorus, and organic carbon did not decrease with distance along the flow path. We did not take water quality samples from the lake to determine if ground water discharge was evident. Data from surface water sampling is difficult to interpret because of changes in geochemistry of water passing through the lake sediments.

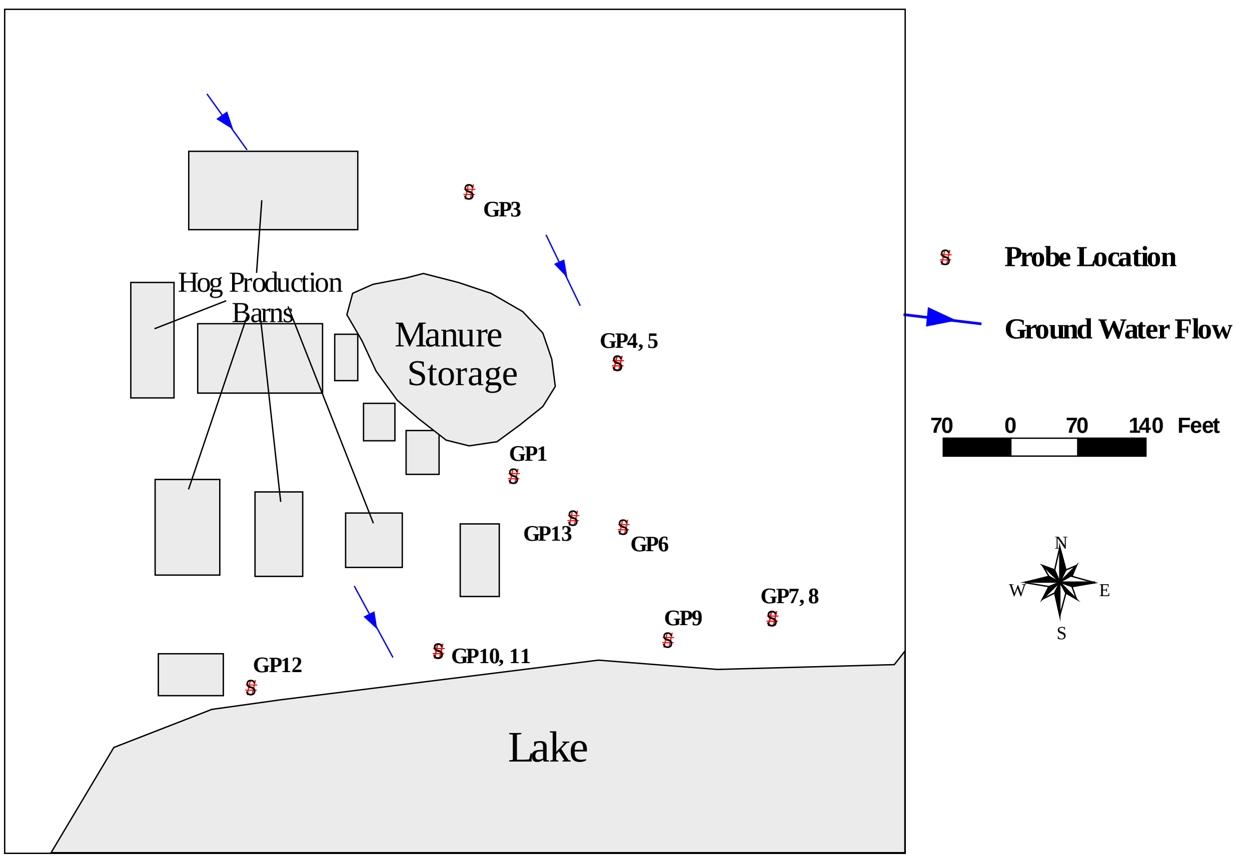

Figure 8: Location of temporary wells and ground water flow direction at Site U1.

Wells 7 and 8 formed a nest, with Well 8 being drilled about five feet below Well 7. Concentrations of ammonia, chloride, Kjeldahl nitrogen, and organic carbon were greater in Well 8, indicating the plume extends below the water table. Concentrations of these chemicals in

Well 7 were similar to concentrations in the up-gradient well (Well 3), indicating the plume is descending in the aquifer.

Well location	Well ID	Ammonia	Chloride	Eh	Iron	Nitrate	Phosphorus
		mg/L	mg/L	mV	mg/L	mg/L	mg/L
Up	3	0.050	17.0	310	0.006	47.3	0.046
Side	4	120	27.6	284	0.020	71.9	0.073
Side	5	83.0	71.9	218	0.297	7.55	0.132
Side	10	1.01	32.3	225	0.005	46.3	0.062
Side	11	0.450	197	77	0.105	0.170	0.199
Side	12	0.510	84.4	141	0.324	0.100	0.148
Down	1	35.4	36.2	312	0.162	62.7	0.085
Down	6	250	179	98	15.7	< 0.020	0.680
Down	7	0.240	19.2	319	0.070	23.6	0.099
Down	8	27.3	63.9	256	0.011	14.6	0.112
Down	9	265	161	129	10.3	< 0.020	1.10
Down	13	151	274	179	1.36	< 0.020	0.361
Well location	**Well ID**	**Potassium**	**Specific conductance**	**Total Kjeldahl nitrogen**	**Total Organic carbon**	**E. coli**	**Average Rank**
		mg/L	**umhos/cm**	**mg/L**	**mg/L**	**MPN/100ml**	
Up	3	2.37	977	0.200	2.80	< 1	0.7
Side	4	39.3	1463	0.100	4.50	< 1	2.4
Side	5	133	2106	86.2	16.4	< 1	7.3
Side	10	41.9	1111	1.09	3.90	< 1	3.2
Side	11	5.81	1853	1.26	7.00	< 1	6.1
Side	12	7.44	1145	1.41	2.60	-	6.0
Down	1	112	1991	374	5.80	< 1	4.2
Down	6	186	3549	270	74.5	< 1	10.0
Down	7	13.4	1055	0.380	2.80	< 1	3.1
Down	8	40.4	1651	29.5	10.7	< 1	5.9
Down	9	181	2860	280	29.4	< 1	9.4
Down	13	17.0	3376	154	28.8	-	7.7

[1] Wells were screened within two feet of the water table, except Wells 5, 8, and 11, which were screened 7 feet below the water table.

Table 9: Summary of water quality at Site U1. Well locations are hydraulically relative to the animal containment area, where Up = up-gradient, Side = side-gradient, and Down = down-gradient.

4.3.2. Site U2

Figure 9 illustrates the location of temporary wells at Site U2. Ground water flow is to the northwest. Table 10 summarizes water quality data for each of the wells.

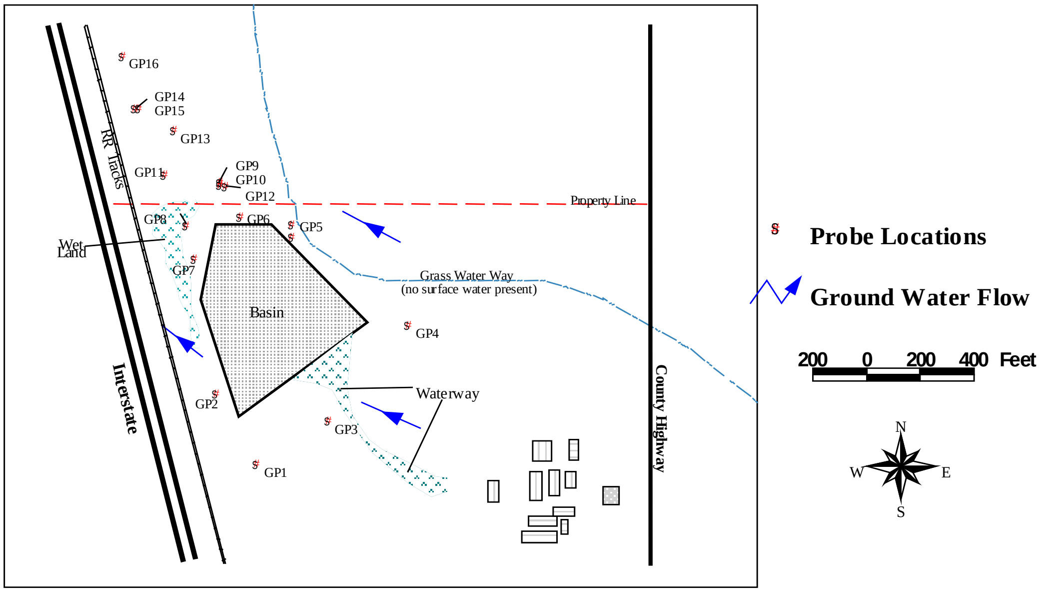

Figure 9: Location of temporary wells and ground water flow direction at Site U2.

Wells 6, 8, 12, and 13, located down-gradient of the manure basin, had the highest ranks (11.7, 10.1, 11.4, and 10, respectively). Wells 1, 3, and 4, located up-gradient of the manure basin, had the lowest ranks (2.6, 3.1, and 2.9, respectively). Impacts from the manure basin are evident in the down-gradient wells. Wells 6 and 8 had high concentrations of Kjeldahl nitrogen and organic carbon compared to the up-gradient wells. Concentrations of nitrogen and organic carbon decreased from Wells 6 and 8 to Wells 12 and 13, indicating attenuation of these chemicals within the aquifer. Wells 14, 15, and 16, which were the furthest down-gradient wells, had slightly higher ranks than the up-gradient wells, but lower ranks than Wells 6, 8, 12, and 13. We estimated a plume to extend to Well 13, a length of about 450 feet.

Concentrations of nitrate were below the reporting limit of 0.020 mg/L in down-gradient wells. Concentrations in up-gradient wells were variable, ranging from 3.8 to 66 mg/L. The variability may be due to proximity of agricultural fields. The data indicate nitrate-reducing conditions down-gradient of the manure storage area.

Subsite	Probe ID	Ammonia	Chloride	Eh	Iron	Nitrate	Sodium
		mg/L	mg/L	mV	mg/L	mg/L	mg/L
Up	4	0.08	13	298	0.029	3.8	6.16
Up	3	0.39	27	246	< 0.0031	66	7.03
Up	1	0.27	22	429	< 0.0031	19	11.7
Side	5	29.1	24	98	9.4	< 0.020	7.34
Down	16	-	5.44	123	-	-	4.86
Down	15	-	28.3	133	-	-	4.94
Down	14	-	39.8	102	-	-	8.57
Down	13	-	41.3	104	-	-	56.9
Down	12	-	110	78	-	-	7.65
Down	11	0.54	160	121	11.9	< 0.020	84.9
Down	9	4.9	220	134	34.8	< 0.020	133
Down	8	0.39	230	113	52.2	< 0.020	157
Down	7	34	100	122	10.7	< 0.020	88.3
Down	6	35.2	220	95	38.8	< 0.020	113
Down	2	136	140	131	3.71	0.020	62.3
Subsite	**Probe ID**	**Specific conductance**	**Total Kjeldahl nitrogen**	**Total Organic carbon**	**Total phosphorus**	**E. coli**	**Average Rank**
		umhos/cm	mg/L	mg/L	mg/L	MPN/100-ml	
Up	1	830	1.8	6.8	1.69	-	2.6
Up	3	1220	0.05	3	0.201	-	3.1
Up	4	580	0.44	5.9	0.841	-	2.9
Side	5	900	28	7.7	0.791	4	7.6
Down	2	1590	153	43	0.91	7	9.3
Down	6	3300	41.7	45	2.2	0	11.7
Down	7	2460	45.2	41	8.06	1	9.0
Down	8	3140	5.01	-	0.79	-	10.1
Down	9	3070	9.79	32	0.222	0	8.8
Down	11	1660	2.27	15	0.399	-	8.7
Down	12	1420	1.43	8.2	0.14	0	11.4
Down	13	1650	1.65	9.7	0.09	0	10.0
Down	14	900	0.33	1.5	0.18	-	8.0
Down	15	790	0.1	1	0.19	-	6.2
Down	16	650	3.46	6.3	5.26	-	4.6

[1] Wells were screened within two feet of the water table, except Wells 10 and 15, which were screened 7 feet below the water table.

Table 10: Summary of water quality at Site U2. Well locations are hydraulically relative to the animal containment area, where Up = up-gradient, Side = side-gradient, and Down = down-gradient.

4.3.3. Site U3

Figure 10 illustrates the location of temporary wells at Site U3. Ground water flow is to the southwest. Table 11 summarizes water quality data for each of the wells.

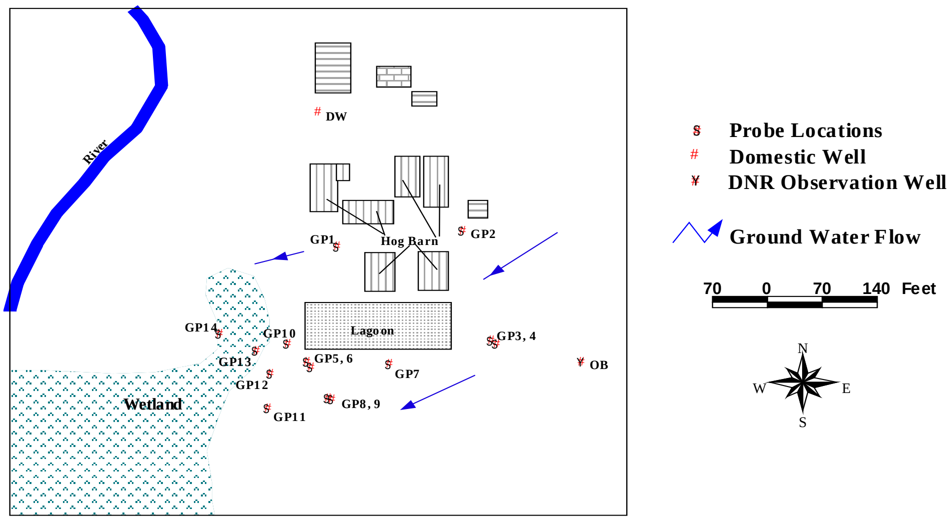

Figure 10: Location of temporary wells and ground water flow direction at Site U3.

Wells 1, 2, and 3, located up-gradient of the unlined basin, had low ranks of 3.9, 5.3, and 4.1, respectively. Wells 5, 6, and 10, the closest down-gradient wells, had high ranks of 11.4, 11.3, and 10.7, respectively. Wells 5 and 6 showed typical impacts from seepage of liquid manure. Eh values were less than 100 mV, nitrate was not detected, concentrations of Kjeldahl nitrogen and ammonia were more than 150 mg/L, and specific conductance was more than twice the value in the up-gradient wells. Wells 13 and 14 appear impacted by the manure basin, since Eh is lower than background, nitrate is not detected, and concentrations of ammonia and Kjeldahl nitrogen are more than ten times greater than concentrations in up-gradient wells. Well 14 is about 125 feet from the unlined basin. A plume extends at least this far.

Concentrations of *E. coli* bacteria do not correlate with the location of the unlined basin. Bacteria were found in Wells 3 and 4, which are up-gradient of the basin, and in Wells 10, 13, and 14, which are the furthest down-gradient wells. No bacteria were found in wells closest to the basin. Bacteria in up-gradient wells may be associated with spreading of manure, although we do not have information on the cropping history of fields adjacent to the manure storage system. Similar results have been observed by other researchers (Libra, personal communication).

Locale	Well ID	Ammonia mg/L	Chloride mg/L	Eh mV	Manganese mg/L	Nitrate mg/L	Specific conductance umhos/cm
Up	1	0.030	24.9	353	23.4	62.5	950
Up	2	0.050	27.0	350	13.3	60.1	963
Up	3	0.11	16.9	350	106	64.8	1300
Up	4	0.41	-	143	534	7.40	643
Down	5	161	79.8	64	1580	< 0.020	2322
Down	6	163	62.4	31	163	< 0.020	2070
Side	7	102	108	240	2530	64.6	2111
Side	8	0.030	1.77	238	7.36	1.20	294
Side	9	0.050	-	256	35.2	22.4	634
Down	10	141	76.2	155	339	4.9	2105
Down	11	0.060	1.21	232	-	< 0.020	281
Down	13	15.0	46.9	-	-	< 0.020	1044
Down	14	1.46	26.0	255	555	< 0.020	902
Locale	**Well ID**	**Sulfate** mg/L	**Total Kjeldahl nitrogen** mg/L	**Total Organic carbon** mg/L	**Total phosphorus** mg/L	**E. coli** MPN/100-ml	**Average Rank**
up	1	14.2	0.36	1.6	0.44	< 1	3.9
up	2	12.7	0.44	3.1	0.50	< 1	5.3
up	3	10.7	0.67	2.0	0.10	4	4.1
up	4	-	0.20	3.4	0.02	1	7.3
side	7	12.0	114	9.7	0.070	< 1	7.7
side	8	1.49	< 0.20	1.4	0.060	< 1	4.3
side	9	-	< 0.20	1.1	0.21	< 1	4.4
down	5	9.66	188	17.1	0.55	< 1	11.4
down	6	9.55	188	25.2	3.56	< 1	11.3
down	10	11.5	166	19.6	1.1	1	10.7
down	11	1.07	0.45	2.2	0.14	< 1	7.2
down	13	15.6	18.7	11.7	0.050	2	8.5
down	14	12.9	2.12	6.0	0.42	3	7.9

[1] Wells were screened within two feet of the water table, except Wells 4, 6 and 9, which were screened 7 feet below the water table.

Table 11: Summary of water quality at Site U3. Well locations are hydraulically relative to the animal containment area, where Up = up-gradient, Side = side-gradient, and Down = down-gradient.

4.4. Summary

Table 12 summarizes estimated plume length and excess 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. As an example of plume development beneath a site with no constructed liner, we illustrate concentrations of nitrate, phosphorus, reduced ammonia, and chloride in a cross-section from Site U2 (Figure 11). A log scale is used in the figure because of the variability in concentrations. Elevated concentrations of reduced nitrogen extend to Well 13, a distance of about 500 feet. Reduced nitrogen (ammonia and organic nitrogen) is attenuated along the plume and is equal to background concentrations in Well 14. Phosphorus concentrations decrease rapidly within the plume and reach background concentrations in Well 9.

Site	Approximate plume length (ft)	Excess down-gradient concentration (mg/L)					
		Ammonia	Nitrate	Total Kjeldahl nitrogen	Phosphorus	Total organic carbon	Potassium
U1	More than 320	265	-23.7	374	1.05	71.7	179
U2	450	136	-66.0	151	6.37	38.2	103
U3	More than 125	163	-60.4	181	3.01	22.1	-

Table 12: Approximate plume lengths and excess chemical concentrations at sites with unlined basins.

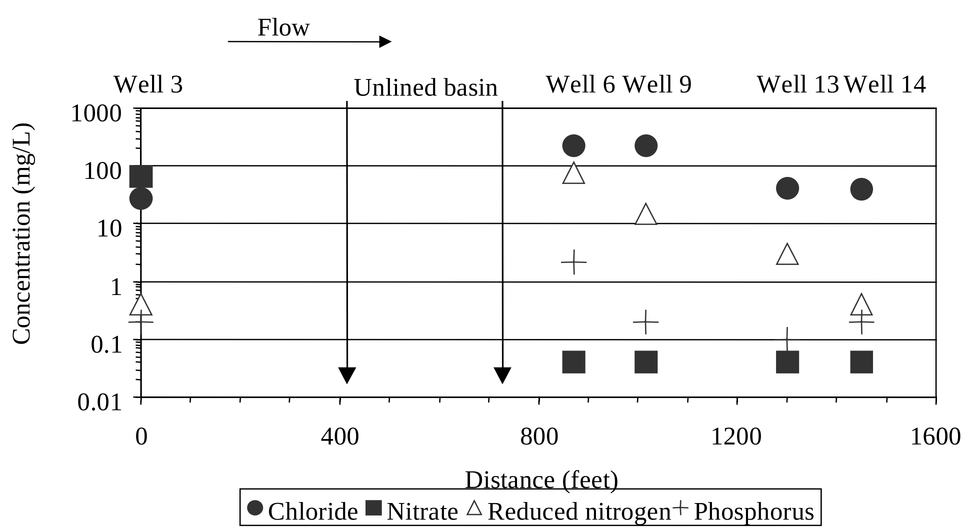

Figure 11: Distribution of chloride, reduced nitrogen, nitrate, and phosphorus along a ground water flow path passing beneath the unlined manure basin at Site U2.

Concentrations of ammonia and phosphorus down-gradient of the unlined basins represent a potential concern if a 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.

5. Manure Storage Basins Constructed with a Cohesive Soil Liner

5.1. Abstract

We conducted three studies to assess impacts of earthen-lined manure systems on ground water quality. In the first study, we sampled ground water adjacent to four earthen-lined basins constructed on coarse-textured soils. We observed plumes down-gradient of the manure basins at each site. At two sites, plumes were characterized by nitrate-reducing conditions, with high concentrations of reduced nitrogen and organic carbon. These plumes extended up to 400 feet from the manure basins. Concentrations of ammonia represented potential concerns if a plume intersected surface water. At the other two sites, we observed oxidizing conditions in plumes. Nitrate was the primary chemical of concern and represented a potential concern if the plume intersected a well. Plume lengths were at least 200 feet at these two sites.

In the second study, we established monitoring networks at 13 sites with newly constructed earthen liners. There was no prior history of manure storage at these sites. Most of the storage systems were constructed in the mid-1990's. Ground water monitoring occurred prior to addition of manure and quarterly since addition of manure. We observed positive correlations between chemical concentrations and sampling event at seven sites. We observed no correlation or negative correlation at six sites. Results are inconclusive and continued monitoring is warranted.

In the third study, lysimeters were installed directly beneath three earthen-lined storage systems. The lysimeters capture liquid manure leachate from the bottom and sidewalls of the storage systems. Inconsistent sampling of the lysimeters in 1998 and 1999 prevented development of a database to understand and determine relationships between leaching rates and water quality. Chemical concentrations were highest in sidewall leachate, presumably because

the sidewalls dried and cracked when liquid manure levels were low in the basins. High specific conductance and high concentrations of chloride characterized the leachate.

5.2. Introduction

Cohesive soil or earthen-lined 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 much lower than through native soil.

Fonstad and Maule (1996) conducted ground water sampling at six hog-manure sites with earthen liners. The systems varied in age from 4 to 20 years. At two 20-year old sites located on tills, ground water plumes were evident down-gradient of the earthen basin. At one site where there was evidence of system failure, ammonia concentrations were very high in soil beneath the basin. Nitrate concentrations in ground water directly beneath the site were 1000 mg/L. At two sites, located on clay soils, there was no evidence of impacts to ground water down-gradient of the basins. At two other sites, located on sandier soils, there was evidence of a ground water plume, characterized by high concentrations of chloride. Gangbazo et al. (1989) installed piezometers directly beneath three dairy and three hog manure storage basins. After 27 months of sampling, they observed decreasing nitrate concentrations and increasing reduced nitrogen concentrations beneath four of the basins, with no detectable trend in the remaining two basins.

Infiltration rates may initially be rapid through an earthen liner because of flow through cracks and fractures in the clay liner. Rapid infiltration is characterized by a breakthrough of chloride (Iowa Department of Natural Resources, 1996; Fonstad and Maule, 1995; Hegg et al., 1979). Gradually, an organic seal forms at the base of the liner. Final infiltration rates are typically 10^{-7} to 10^{-8} cm/s. Gradually, over many years, the infiltration rate may eventually increase again as the integrity of the liner decreases. This may occur through development of secondary porosity, such as occurs with drying and cracking of sidewalls and animal burrowing. Plumes typically develop in ground water under coarse soils. Elevated chloride and ammonia concentrations provide evidence of impacts from an earthen liner (Roswell et al., 1985; Miller et al., 1985). Maule and Fonstad (1996) conducted modeling studies for coarse-textured soils and estimated plume lengths of about 110 feet for chloride and 45 feet for ammonia after

20 years. An important factor is the cation exchange capacity (CEC) of soils that make up the liner, which provides a measure of the likelihood that ammonia will be adsorbed. Barrington and Broughton (1988) observed rapid contamination of ground water with ammonia when the CEC of the liner was less than 30 meq/100 g, which corresponded to a clay content of about 30 percent. Phillips et al. (1983) observed only small quantities of phosphorus, ammonia, and nitrate moving through two bottom loaded earthen basin liners containing dairy waste. Barrington et al. (1987) observed seepage through laboratory cores containing sandy soils mixed with manure. Concentrations of total organic carbon, potassium, chloride, and total nitrogen in seepage water were 375, 1300, 175, and 375 mg/L, respectively. Terry et al. (1981) observed rapid decreases in nitrate concentration, to near background concentrations, within 300 feet of earthen basins.

5.3. Monitoring in Minnesota

Extensive monitoring has been conducted on earthen-lined systems in Minnesota. These include sampling of temporary wells, leachate collection systems, permanent monitoring well networks, and perimeter tile line effluent.

5.3.1. Sampling of Temporary Wells

We selected three sites for ground water sampling. Table 13 summarizes characteristics of these sites. Figure 12 illustrates the location of these sites. All sites are located on coarse-textured soils in central Minnesota. This is an area where livestock production occurs extensively in sensitive hydrogeologic environments.

Site	Animal	Animal units	Years of operation	Depth to water (ft)[1]	Soil
E1[2]	Dairy	150	10	8 to 15	Coarse sand/gravel
E2	Dairy	130	6	30 to 40	Sand
E3	Dairy/beef	175	12	45 to 55	Sandy loam

[1] These depths represent the range of depths encountered during drilling of temporary wells.
[2] Site E1 has two storage basins.

Table 13: Characteristics of sites with earthen liners.

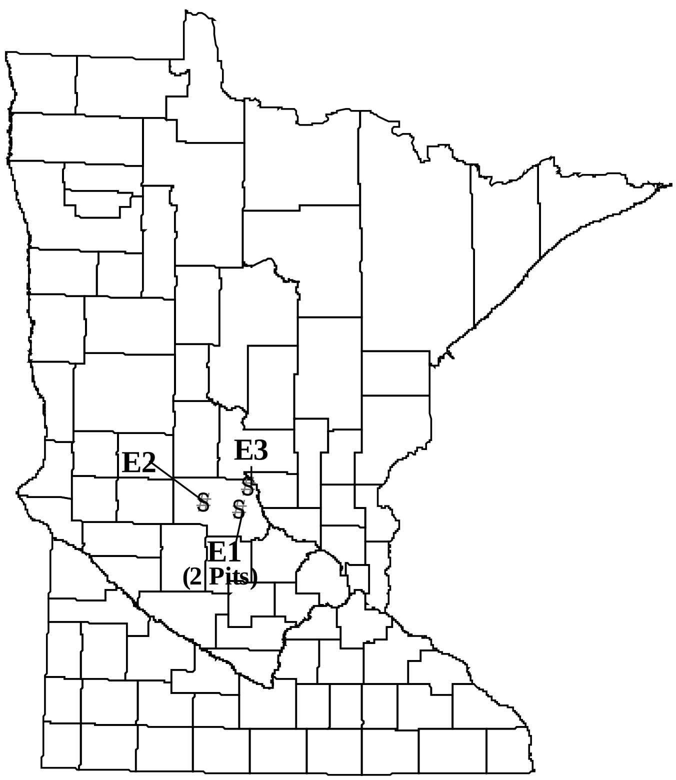

Figure 12: Location of sites with earthen-lined storage systems.

5.3.1.1. Site E1

Figure 13 illustrates the location of temporary wells at Site E1. Two basins are present at this site. Ground water flow is to the southwest. Table 14 summarizes water quality data for each of the wells. This storage system receives primarily solid manure.

Well 7, located immediately down-gradient of Basin 1, showed impacts from manure storage. Concentrations of ammonia, chloride, dissolved organic carbon, phosphorus, and Kjeldahl nitrogen were 66, 94, 39, 0.55, and 77 mg/L, respectively. This compares with concentrations of 0.05, 8.1, 1.0, 0.04, and 0.3, respectively, in Well 2, which was up-gradient of the feedlot. The Eh in Well 7 was very low (73 mV), while iron concentrations were high (22.4 mg/L), reflecting nitrate-reducing conditions. Well 6, which formed a nest with Well 7, was drilled five feet deeper than Well 7. No water quality impacts were evident in Well 6. A plume extends to Well 19, since concentrations of ammonia in this well were 8.78 mg/L. Well 19 was located about 275 feet from the center of Basin 1.

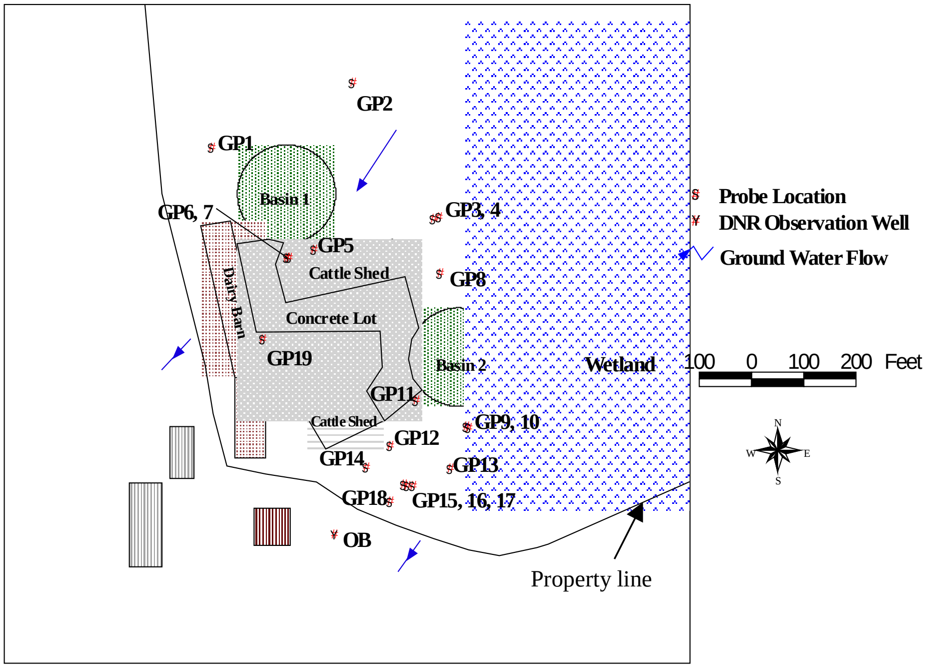

Figure 13: Location of temporary wells and ground water flow direction at Site E1.

At Basin 2, ranks were high in down-gradient Wells 12, 14, and 17 (13.3, 12.4, and 13.7, respectively). Ranks were low in up-gradient Wells 3, 4, and 8 (5.9, 8.1, and 9.0, respectively). Eh was less than 139 mV in each of the down-gradient wells, indicating nitrate-reducing conditions. Well 18, located about 400 feet from the center of the basin, appeared impacted by the basin. Eh in this well was 165 mV, compared to 262 mV in Well 3. The concentration of ammonia in Well 18 was 1.23 mg/L. We estimated plume length to be more than 400 feet from the center of the basin.

Wells 15, 16, and 17 formed a nest. Water quality impacts were evident in Wells 16 and 17, which were drilled about four and eight feet deeper, respectively, than Well 15. Well 15 did not appear impacted, with ammonia and chloride concentrations similar to those in up-gradient wells. Wells 16 and 17 showed impacts, with ammonia concentrations greater than 1 mg/L and chloride concentrations greater than 69 mg/L. Ground water recharge down-gradient of the basin is probably pushing the plume deeper into the aquifer. Dilution does not appear to be an important mechanism of attenuation, since concentrations of chemicals in Wells 16 and 17 are similar to other down-gradient wells.

Well location	Well ID	Basin	Ammonia	Chloride	Eh	Iron	Nitrate	Phosphorus
			Mg/L	mg/L	mV	mg/L	mg/L	mg/L
Up	2	1	0.05	8.1	271	0.018	3.78	0.04
Side	1	1	0.05	10.1	268	0.030	4.44	0.02
Down	5	1	0.34	-	243	0.006	3.39	0.02
Down	6	1	0.08	11.6	223	1.03	2.06	1.53
Down	7	1	66.16	93.7	73	22.4	0.02	0.55
Down	19	1	8.78	43.3	236	0.061	0.06	0.02
Up	3	2	0.05	6.4	262	0.032	4.60	0.02
Up	4	2	0.16	39.3	270	0.015	4.58	0.02
Up	8	2	0.83	26.2	182	4.53	0.66	0.15
Side	9	2	0.02	114.6	139	11.1	< 0.020	0.92
Side	10	2	4.17	28.5	59	1.33	< 0.020	0.54
Side	13	2	3.64	35.2	81	5.02	< 0.020	3.66
Down	11	2	1.01	29.1	114	13.6	< 0.020	0.27
Down	12	2	1.82	120.7	93	0.039	0.48	0.02
Down	14	2	0.24	28.4	126	2.06	3.79	0.74
Down	15	2	0.10	27.9	257	0.127	0.53	0.02
Down	16	2	0.36	69.1	45	4.06	< 0.020	0.38
Down	17	2	1.02	71.6	45	5.05	< 0.020	0.88
Down	18	2	1.23	21.8	165	3.04	< 0.020	0.79

Well location	Well ID	Basin	Potassium	Specific conductance	Total Kjeldahl nitrogen	Total Organic carbon	E. coli	Average Rank
			mg/L	umhos/cm	mg/L	mg/L	MPN/100ml	
Up	2	1	2.2	542	0.3	2.0	-	6.0
Side	1	1	2.9	629	0.5	2.3	-	5.9
Down	5	1	27.0	997	0.9	-	-	8.0
Down	6	1	2.1	546	0.2	1.2	-	8.2
Down	7	1	53.8	1679	76.9	40.9	-	13.4
Down	19	1	14.7	882	10.9	6.1	0	8.3
Up	3	2	1.5	580	0.3	1.5	-	5.9
Up	4	2	3.5	531	1.0	5.4	-	8.1
Up	8	2	1.7	1235	3.1	27.1	-	9.0
Side	9	2	66.3	2252	0.1	50.1	-	13.0
Side	10	2	24.7	1097	6.6	25.6	-	10.5
Side	13	2	42.7	1480	7.1	38.6	95	13.0
Down	11	2	4.1	891	2.5	20.0	-	9.6
Down	12	2	200.6	1454	6.0	39.7	18	13.3
Down	14	2	137.6	637	3.6	34.8	-	12.4
Down	15	2	23.7	481	2.3	22.0	-	6.7
Down	16	2	43.6	769	2.9	25.6	-	10.9
Down	17	2	95.1	836	3.1	42.6	0	13.7
Down	18	2	81.8	820	3.4	22.3	0	10.4

[1] Wells were screened within two feet of the water table, except Wells 4, 6, 10 and 16, which were screened 7 feet below water table, and Well 17, which was screened 10 feet below the water table.

Table 14: Summary of water quality at Site E1. Well locations are hydraulically relative to the animal containment area, where Up = up-gradient, Side = side-gradient, and Down = down-gradient.

5.3.1.2. Site E2

Figure 14 illustrates the location of temporary wells at Site E2. Ground water flow is to the southwest. Table 15 summarizes water quality data for each of the wells.

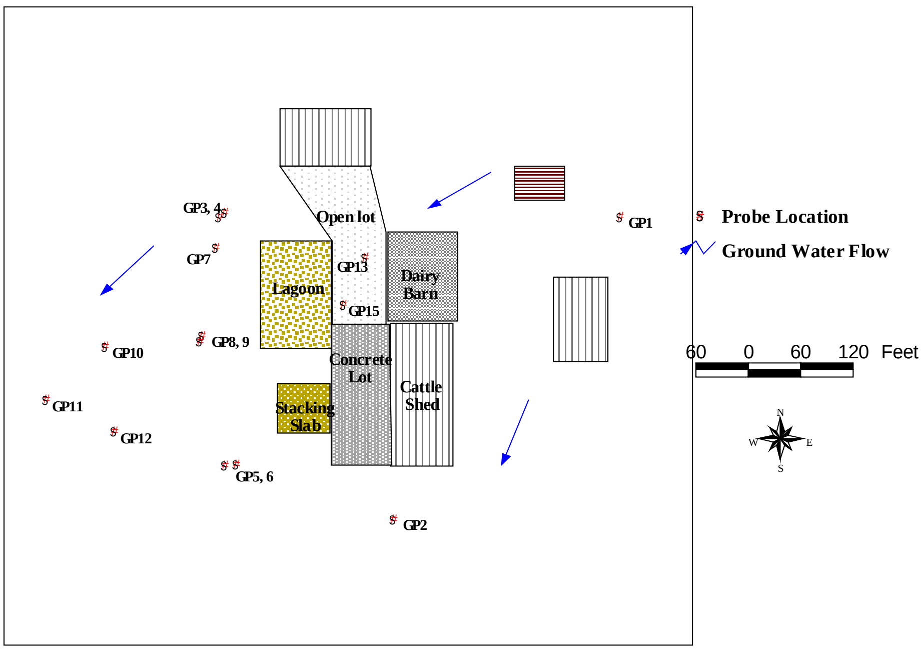

Figure 14: Location of temporary wells and ground water flow direction at Site E2.

A plume was evident at Site E2, but the characteristics of this plume differed from the two plumes at Site E1. High concentrations of nitrate, chloride, and a high specific conductivity characterize the plume at Site E2. The nitrate concentration in Well 8, the down-gradient well closest to the manure basin, was 81 mg/L, compared to a median concentration of 34 mg/L in up-gradient wells. The specific conductance in Well 8 is about twice that in up-gradient wells, and the chloride concentration is about three times greater than concentrations in up-gradient wells. Concentrations of organic carbon and reduced nitrogen in down-gradient wells (Wells 8, 10, and 11) are similar to concentrations in up-gradient wells (Wells 1, 13, and 15). A plume extends to Well 11, a distance of about 300 feet. The nitrate concentration of 48 mg/L in Well 11 was 14 mg/L more than the median concentration in up-gradient wells.

Well location	Well ID	Ammonia	Chloride	Dissolved oxygen	Eh	Iron	Nitrate
		mg/L	mg/L	mg/L	mV	mg/L	mg/L
Up	1	0.080	27.1	10.84	262	0.0201	18.2
Up	13	0.08	27.8	4.40	291	0.0051	39.1
Up	15	0.15	27.0	2.26	285	0.0126	34.0
Side	3	0.090	31.1	11.36	335	< 0.0031	34.5
Side	4	0.10	30.8	0.95	300	0.0428	11.8
Side	5	0.10	27.5	5.71	305	0.0256	29.6
Side	6	0.10	20.9	1.43	288	0.0244	25.7
Down	8	0.13	80.5	9.92	284	0.0061	83.0
Down	7	0.18	54.2	9.31	289	0.0034	49.9
Down	9	0.11	28.7	6.29	266	0.0476	44.5
Down	10	0.11	50.2	10.44	284	< 0.003	55.4
Down	11	0.12	45.9	11.16	279	< 0.003	48.4
Down	12	0.09	37.6	8.38	288	< 0.003	49.8
Well location	**Well ID**	**Potassium**	**Specific conduct-ance**	**Total Kjeldahl nitrogen**	**Total Organic carbon**	**Total phosphorus**	**Average Rank**
		mg/L	**umhos/cm**	**mg/L**	**mg/L**	**mg/L**	
Up	1	19.6	928	0.67	2.8	0.030	6.9
Up	13	3.12	966	0.45	2.5	0.15	5.9
Up	15	15.3	1032	0.54	2.4	0.090	7.5
Side	3	6.91	975	0.56	2.9	0.060	4.9
Side	4	6.93	848	0.60	3.2	0.040	8.3
Side	5	9.74	1104	0.43	2.6	0.060	7.4
Side	6	2.77	888	0.45	1.8	0.060	6.6
Down	8	9.29	1706	0.76	3.9	0.060	8.7
Down	7	6.46	1369	0.93	4.7	0.040	7.8
Down	9	3.99	1055	0.43	1.8	0.030	7.2
Down	10	8.13	1277	0.72	3.4	0.030	6.6
Down	11	11.0	1240	0.65	4.5	0.030	7.4
Down	12	4.78	1188	0.26	2.4	0.050	5.6

[1] Wells were screened within two feet of the water table, except Wells 4, 6, and 9, which were screened 7 feet below water table.

Table 15: Summary of water quality at Site E2. Well locations are hydraulically relative to the animal containment area, where Up = up-gradient, Side = side-gradient, and Down = down-gradient.

The depth to water at Site E2 is about 35 feet. Consequently, the bottom of the manure basin is far above the water table. Leachate passing through the basin must travel through a thick unsaturated zone. Unsaturated conditions may occur within the vadose zone, resulting in oxidizing conditions in which ammonia is converted to nitrate.

5.3.1.3. Site E3

Figure 15 illustrates the location of temporary wells at Site E3. Ground water flow is to the northeast. Table 16 summarizes water quality data for each of the wells.

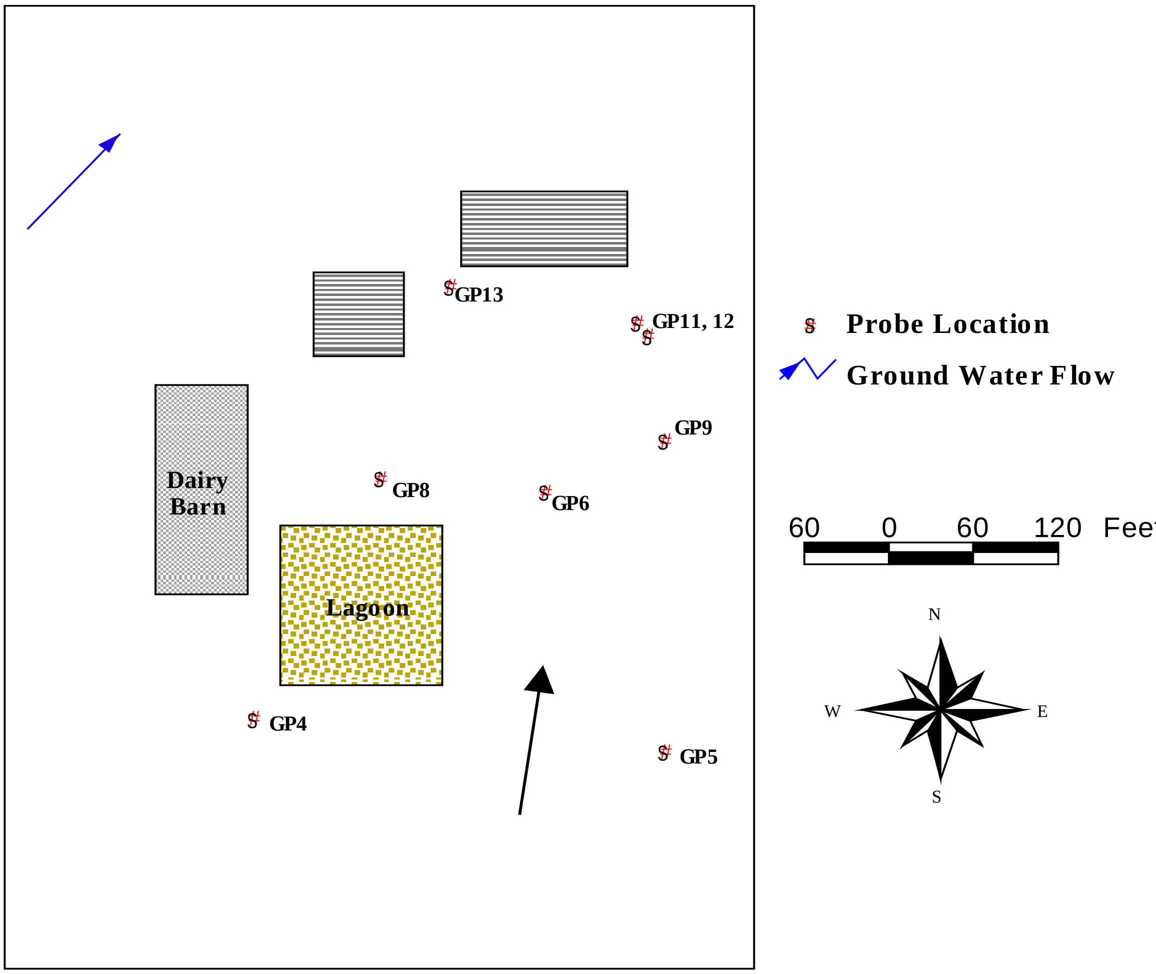

Figure 15: Location of temporary wells and ground water flow direction at Site E3.

Well 8, located down-gradient of the storage system, had ammonia, chloride, total nitrogen, and organic carbon concentrations of 4.81, 22.5, 7.39, 39.2, and 1.26 mg/L, respectively. These were higher than concentrations of 0.24, 13.3, 1.14, 26.5, and 0.15 mg/L, respectively, in Well 5, which is up-gradient of the storage system. The high iron concentration of 4.6 mg/L in Well 8 indicates the presence of nitrate-reducing conditions down-gradient of the aquifer. Chloride concentrations in Well 11 were similar to those in Well 8, indicating a plume extended to Well 11. Concentrations of ammonia, total nitrogen, phosphorus, and organic carbon were lower in Well 11 than in Well 8, however, indicating some attenuation of these chemicals within the plume. Well 12, which forms a nest with Well 11, showed no impacts from the manure storage system. There was no evidence of the plume moving deeper into the underlying aquifer.

Well location	Well ID	Ammonia	Chloride	Dissolved organic carbon	Dissolved oxygen	Iron	Nitrate
		mg/L	Mg/L	mg/L	mg/L	mg/L	mg/L
Up	4	0.360	21.0	6.00	10.7	0.004	2.30
Up	5	0.240	13.3	2.20	-	0.006	4.00
Down	6	0.260	22.6	-	9.50	0.007	3.40
Down	8	4.810	22.5	6.80	4.70	4.603	10.0
Down	9	0.290	20.3	-	8.50	0.029	10.6
Down	10	0.300	16.9	1.90	6.40	-	4.90
Down	11	0.510	24.9	1.90	6.90	0.015	4.90
Down	12	0.090	5.30	-	8.61	0.360	3.90
Down	13	0.500	13.1	6.10	-	0.006	1.40
Well location	**Well ID**	**Phosphorus**	**Potassium**	**Sulfate-S**	**Total Kjeldahl nitrogen**	**Total Organic carbon**	**Average Rank**
		mg/L	mg/L	mg/L	mg/L	mg/L	
Up	4	0.41	4.03	2.14	1.70	33.7	3.8
Up	5	0.15	1.65	2.81	1.14	26.5	6.1
Down	6	0.35	1.90	4.50	1.94	20.3	4.9
Down	8	1.26	6.07	4.72	7.39	29.2	2.0
Down	9	0.25	1.99	3.73	1.13	24.7	5.1
Down	10	-	-	4.93	2.57	21.5	5.0
Down	11	0.47	3.02	4.70	2.25	21.5	3.4
Down	12	-	2.70	-	0.10	-	-
Down	13	0.27	3.19	3.64	3.46	28.7	4.1

[1] Wells were screened within two feet of the water table, except Well 12, which was screened 7 feet below the water table.

Table 16: Summary of water quality at Site E3. Well locations are hydraulically relative to the animal containment area, where Up = up-gradient, Side = side-gradient, and Down = down-gradient.

The nitrate concentration in Well 8 was 10 mg/L, compared to a concentration of 4.0 mg/L in the up-gradient well (Well 5). The high concentrations of reduced nitrogen and nitrate in Well 8 compared to the up-gradient well appear contradictory. The well had high concentrations of iron and dissolved oxygen, another contradiction. Either the ground water system beneath and immediately down-gradient of the liner is out of equilibrium with respect to nitrogen, or our sampling data is in error. We have observed high concentrations of nitrate and ammonia in one well at an open feedlot (see Figure 49), however, indicating that ground water can be out of equilibrium with respect to nitrogen.

5.3.1.4.Summary

Table 17 shows excess concentrations of ammonia, Kjeldahl nitrogen, phosphorus, potassium, nitrate, and organic carbon in down-gradient wells at the sites with earthen liners. Estimates of plume length are included in Table 17. 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. Excess concentrations of ammonia (66.1 mg/L) and organic nitrogen (76.6 mg/L) were particularly high down-gradient of Basin 1. At Sites E2 and E3, nitrate concentrations down-gradient of the manure basins exceeded concentrations in up-gradient wells. At these two sites, unsaturated zone thickness exceeded 20 feet. Consequently, unsaturated flow may occur during leaching to ground water, resulting in conversion of ammonia to nitrate. Nitrate is mobile in water and nitrate plumes developed at these two sites.

Plumes extended for approximate distances of 275 to 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.

Site	Approximate plume length (ft)	Excess down-gradient concentration (mg/L)					
		Ammonia	Total Kjeldahl nitrogen	Phosphorus	Total organic carbon	Nitrate	Potassium
E1: basin 1	275	66.1	76.6	1.49	38.9	-0.39	51.6
E1: basin 2	400	3.24	4.00	3.51	23	-0.80	19.7
E2	325	4.03	0.26	-0.09	1.90	43.9	-4.30
E3	320	4.45	5.69	1.26	0.80	8.30	2.04

Table 17: Approximate plume lengths and excess chemical concentrations at sites with earthen liners.

5.3.2. Investigations at Sites with Permanent Monitoring Wells or Tile Lines

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 three 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. Figure 16 illustrates the location of the sites. Table 18 summarizes the characteristics of each site.

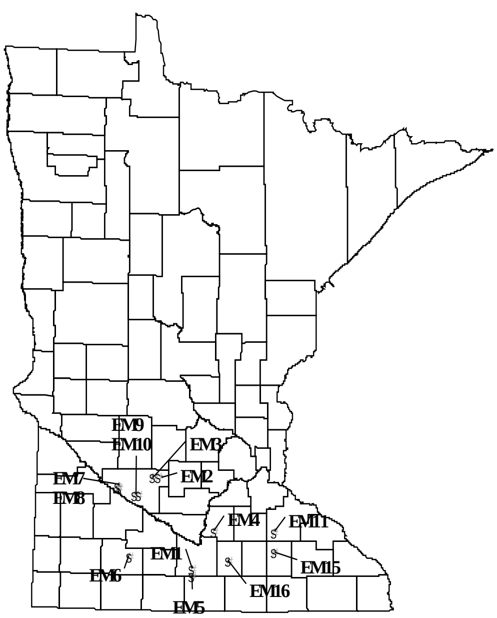

Figure 16: Location of sites having earthen-lined basins and permanent monitoring networks.

Site	Approx. Date Manure First Added	Livestock	Animal Units	Wells	Tile lines
EM1	10/94	Hogs	4800	X	
EM2	9/94	Hogs	2338	X	
EM3	9/94	Hogs	3040	X	X
EM4	12/94	Dairy	700	X	
EM5	11/94	Hogs	4800	X	X
EM6	4/95	Hogs	-	X	
EM7	4/95	Hogs	-	X	
EM8	8/95	Hogs	-	X	X
EM9	9/94	Hogs	-	X	X
EM10	7/94	Hogs	-	X	X
EM11	12/95	Dairy	700		X
EM15	1/95	Hogs	8000		X
EM16	4/96	Hogs	4800		X

Table 18: Summary information for sites with permanent monitoring networks. There were insufficient data for Sites EM12, EM13, and EM14 to include in the discussion, and they were thus omitted from the table.

5.3.2.1. Site EM1

Site EM1, located in Blue Earth County, consists of five 41 X 200 foot total confinement barns and a two-stage earthen basin system. There are 4800 animal units consisting of grower and finishing hogs. Six monitoring wells surround the two basins. Baseline monitoring began on August 19, 1994. Three sampling events occurred prior to addition of manure on October 31, 1994. Quarterly sampling began in spring, 1995. Figure 17 illustrates the location of manure basins and monitoring wells.

Wells 1 and 2 represented water quality down-gradient of the manure storage system. Wells 4 and 5 represented water quality up-gradient of the manure storage system. Using nonparametric methods, we calculated 90% confidence tolerance limits (Loftis et al., 1987). There were no significant differences in concentrations of sulfate, chloride, nitrate, ammonia, and specific conductance between up-gradient and down-gradient wells.

We calculated correlation coefficients (nonparametric) between sampling event and chemical concentrations. Sampling events are assigned continuous numbers starting with the first event. Significant negative correlations were observed in Well 6 between sampling event and concentrations of sulfate, chloride, nitrate, and specific conductance (Table 19). Negative correlations with sampling event were observed in Well 2 for sulfate and nitrate, and in Well 1 for sulfate and chloride. Positive correlations with sampling event were observed in Wells 1 and 2 for specific conductance.

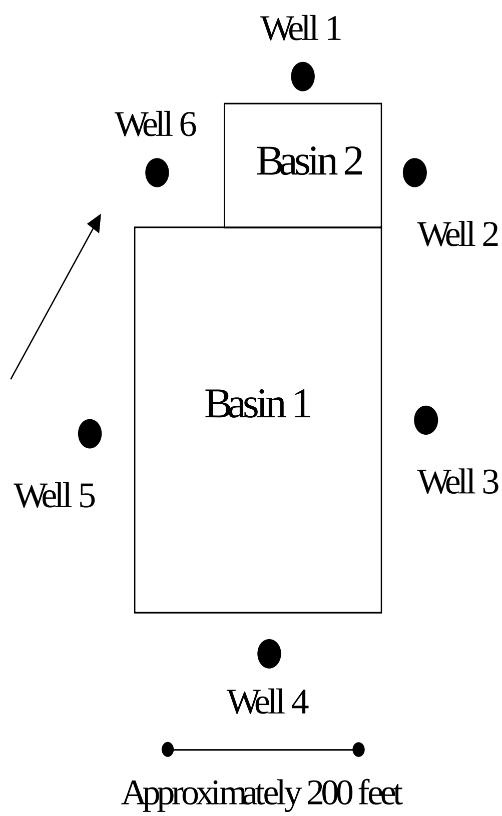

Figure 17: Location of monitoring wells, storage basins, and ground water flow direction (arrow) at Site EM1.

Well	Sulfate	Chloride	Specific Conductance	Nitrate	Ammonia
1	-0.777	-0.746	0.468	0.366	0.184
2	-0.606	-0.169	0.455	-0.912	0.166
3	-0.513	-0.046	0.145	0.489	0.322
4	-0.335	-0.002	0.246	-0.107	0.041
5	-0.050	-0.564	0.367	-0.212	0.263
6	-0.632	-0.764	-0.611	-0.908	0.338

Table 19: Correlation coefficients between sampling event and chemical concentrations at Site EM1

5.3.2.2. Site EM2

Site EM2, located in Renville County, is a hog production facility that includes a 77 X 327 foot gestation barn, a 71 X 192 foot total confinement farrowing barn, and a two-stage earthen basin system. There are 2338 animal units at the site. Three monitoring wells surround the two basins. Baseline monitoring began on April 29, 1994. Five sampling events occurred prior to addition of manure. Quarterly sampling began in January 1995. Figure 18 illustrates the location of manure basins and monitoring wells.

Well 3 represented water quality down-gradient of the manure storage system and Well 1 was up-gradient. Using nonparametric methods, we calculated 90% confidence tolerance limits. We observed no significant differences in concentrations of sulfate, chloride, nitrate, ammonia, and specific conductance between up-gradient and down-gradient wells. There was a positive correlation between sampling event and concentrations of nitrate and chloride in Well 3 (Table 20).

There is strong evidence ($p < 0.002$) of seasonality in nitrate and chloride concentrations in Well 3, particularly since 1997 (Figure 19)[9]. Concentrations were highest during the summer and fall and lowest in winter. There were no significant correlations between concentrations of other chemicals and concentrations of either chloride or nitrate. Potential explanations include removal of manure during certain times of the year, local hydrologic conditions that affect the distribution of chemicals in ground water, or changes in microbial activity in response to temperature changes (applicable only to nitrate).

[9] We divided data into winter, spring, summer, and fall events, then used the Kruskal-Wallis test to compare concentrations between these seasons.

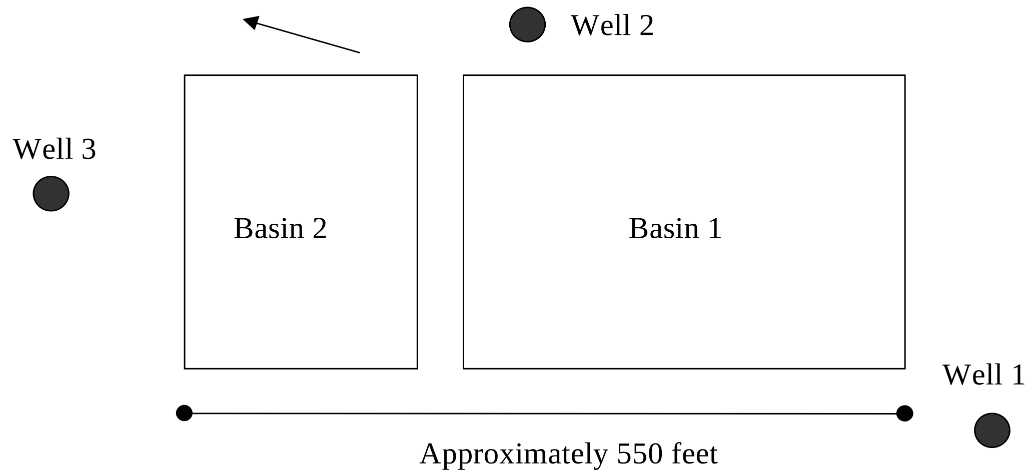

Figure 18: Location of manure storage basins, monitoring wells, and ground water flow direction (arrow) at Site EM2.

Well	Sulfate	Chloride	Nitrate	Total Kjeldahl nitrogen
1	-0.124	0.158	-0.255	-
2	0.194	0.095	-0.345	0.447
3	-0.271	0.605	0.812	0.228

Table 20: Correlation coefficients between sampling event and chemical concentrations at Site EM2.

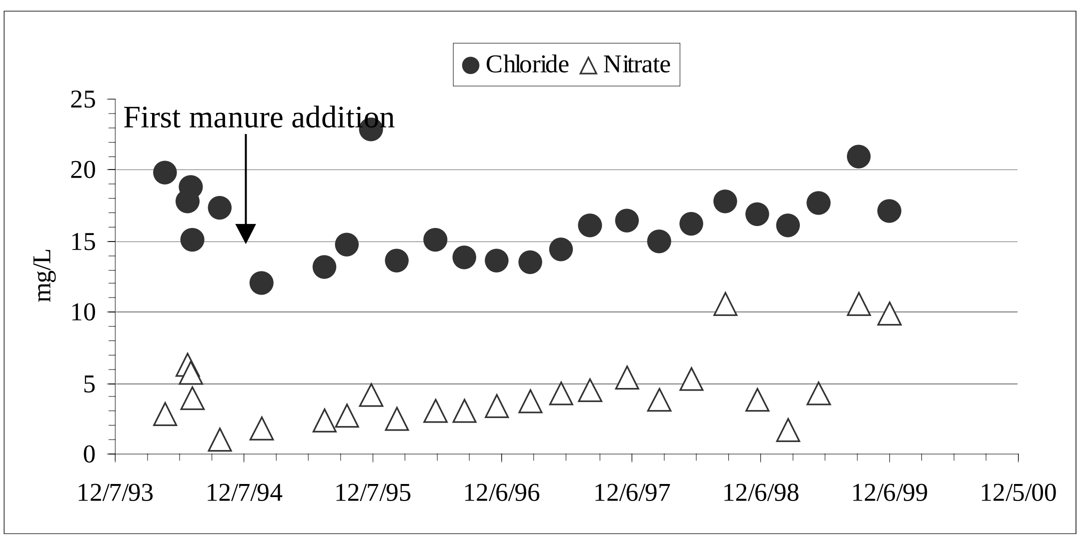

Figure 19: Concentrations of chloride and nitrate as a function of sampling date in Well 3 at Site EM2.

5.3.2.3. Site EM3

Site EM3, located in Renville County, is a hog production facility that includes a 71 X 184 foot total confinement nursery, four 41 X 200 foot total confinement finishing barns, and a two-stage earthen basin system. There are 3040 animal units at the site. Five monitoring wells surround the two basins. A perimeter tile surrounds the facility. The tile line and wells were installed in 1994. Baseline monitoring began on June 29, 1994. Seven sampling events occurred prior to addition of manure. Quarterly sampling began in spring, 1995. Figure 20 illustrates the location of manure basins, monitoring wells, and the tile line.

Monitoring Well 1 represented up-gradient water quality, while Wells 3 and 5 represented water quality down-gradient of the manure basins. Using nonparametric methods, we calculated the 90 percent confidence tolerance limits. The difference in ranked chloride concentration (17.0) exceeded the tolerance limit of 16.1 for the last sampling event in 1999 (Figure 21).

To further explore potential impacts from the basins, we calculated nonparametric correlation coefficients between sampling parameters and sampling event (Table 21). There was a negative correlation between sampling event and concentrations of ammonia and nitrate in Well 3. Well 5, which is down-gradient of the manure basin, showed a strong negative correlation (-0.925) between sampling event and chloride concentration.

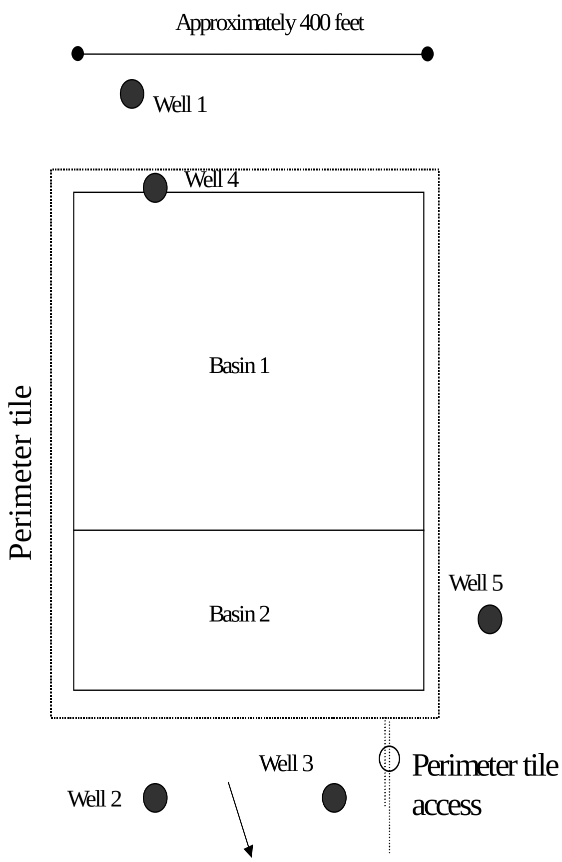

Figure 20: Location of monitoring wells, tile lines, storage basins, and ground water flow direction (arrow) at Site EM3.

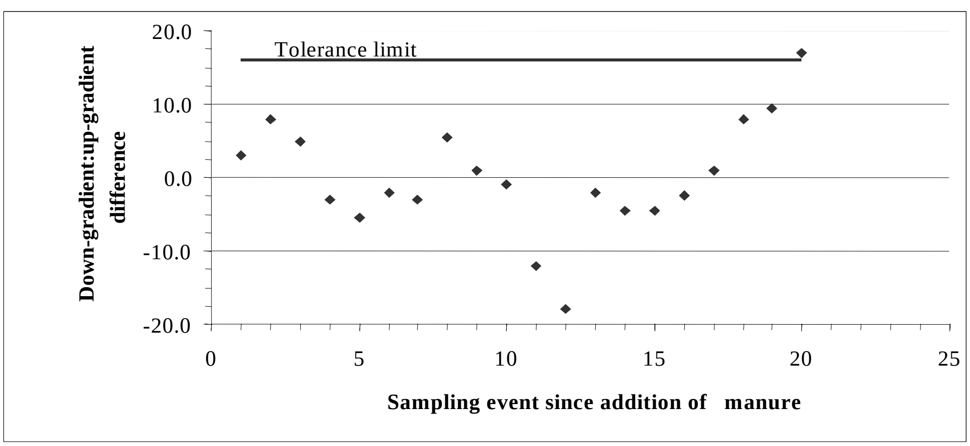

Figure 21: Difference between down-gradient (Wells 3 and 5) and up-gradient (Well 1) ranked concentrations of chloride at site EM3 since addition of manure. The 90 percent tolerance limit is included in the plot.

Well	Sulfate	Chloride	Nitrate	Total Kjeldahl nitrogen	Ammonia
1	-0.313	0.679	0.229	0.115	-0.764
3	-0.315	0.290	-0.642	0.174	-0.521
4	0.236	-0.213	-0.730	0.492	-
5	0.148	-0.925	-0.019	0.094	0.049

Table 21: Correlation coefficients between sampling event and chemical concentrations at Site EM3.

Concentrations of sulfate and chloride in the tile line were positively correlated (R^2 = 0.664 for sulfate and 0.514 for chloride) with sampling event, indicating increasing concentrations during the sampling period. Flow information was not available for the tile line. There were no seasonal differences in concentrations of chloride and sulfate. Figure 22 indicates the concentration of chloride has increased steadily since July 1997. The results suggest that the tile line may be intercepting ground water from the storage basin.

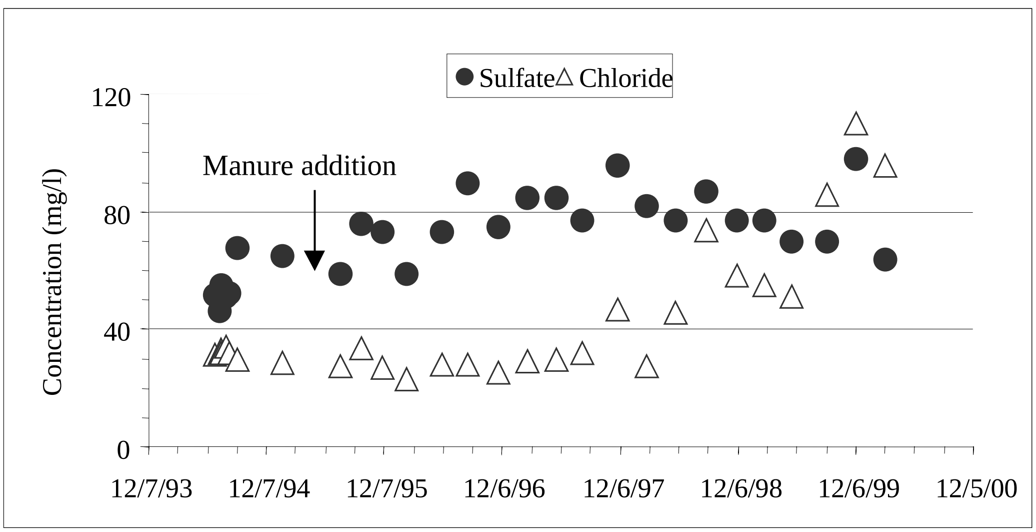

Figure 22: Concentrations of chloride and sulfate in the perimeter tile at Site EM3.

5.3.2.4. Site EM4

Site EM4, located in Le Sueur County, is a dairy operation that includes four 112 X 212 foot total confinement barns, a 50 X 250 foot milking parlor, a 40 X 60 foot total confinement cattle barn, and a two-stage earthen basin system. There are 700 animal units at the site. Three monitoring wells surround the two basins. Baseline monitoring began on May 25, 1994. Three sampling events occurred prior to addition of manure. Manure was added to the basin in the fall of 1995. Figure 23 illustrates the location of manure basins and monitoring wells.

Ground water flow direction has not been consistent at the site, making it difficult to determine which wells are up-gradient and down-gradient of the manure basin. Only one to three samples were collected each year since sampling began in 1996. There was no correlation between sampling event and chemical concentrations in wells.

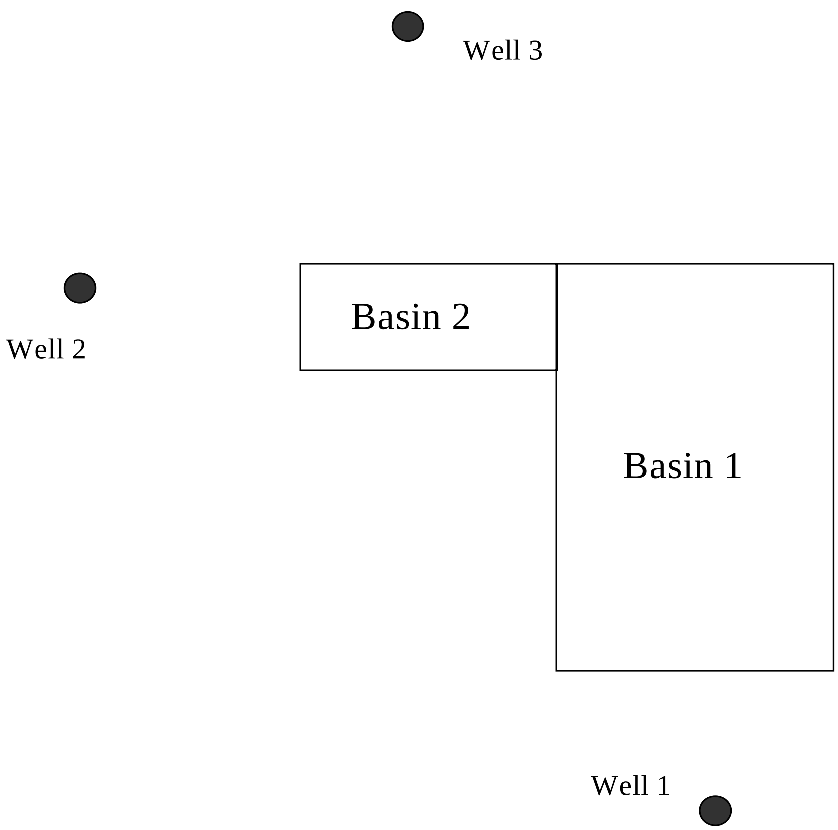

Figure 23: Location of wells and manure basins at Site EM4. Ground water flow direction is unknown.

5.3.2.5. Site EM5

Site EM5, located in Blue Earth County, consists of five total confinement barns and a two-stage earthen basin system. Five monitoring wells surround the two basins. A tile line exists around the basins. Baseline monitoring began on September 1, 1994. Three sampling events occurred prior to addition of manure. Quarterly sampling began in spring, 1995. Figure 24 illustrates the location of manure basins and monitoring wells.

Monitoring Well 4 represented up-gradient water quality, while Well 2 represented down-gradient water quality. Using nonparametric methods, we calculated 90 percent confidence tolerance limits. We observed no significant differences in concentrations of sulfate, chloride, nitrate, specific conductance, total Kjeldahl nitrogen, and ammonia.

We calculated nonparametric correlation coefficients between sampling event and chemical concentration. Table 22 summarizes results of this analysis. The data reveal no significant correlations between sampling event and chemical concentrations in the down-gradient well (Well 2).

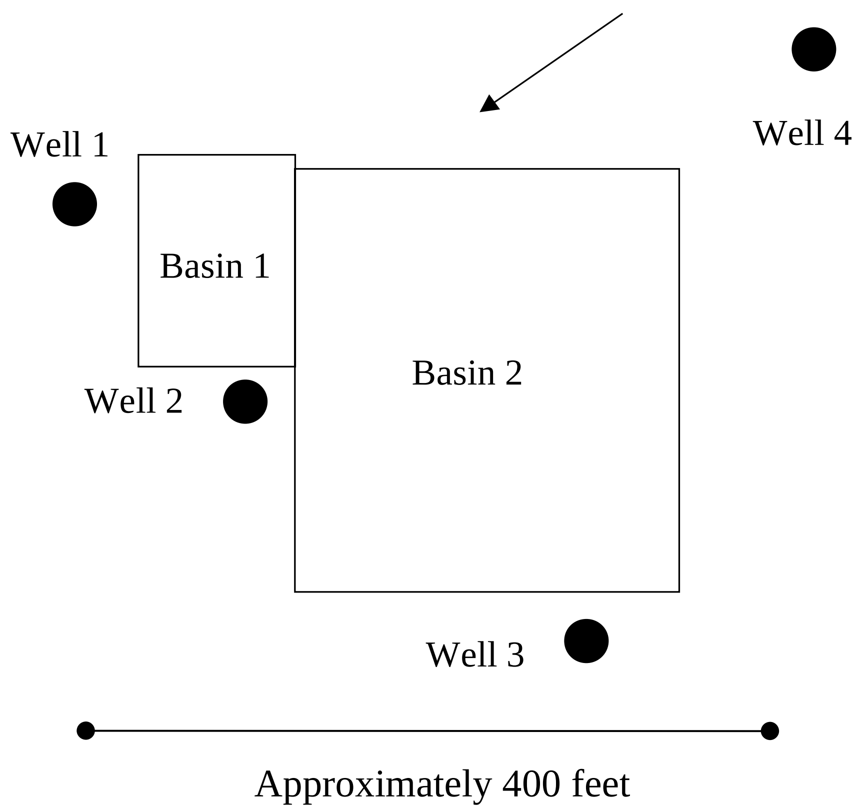

Figure 24: Location of monitoring wells, manure basins, and ground water flow direction (arrow) at site EM5.

Well	Sulfate	Chloride	Nitrate	Total Kjeldahl nitrogen	Specific conductance	Ammonia
1	0.561	0.159	-0.767	-0.137	-0.167	-0.274
2	-0.400	-0.377	-0.467	0.000	-0.400	0.235
3	-0.450	-0.950	0.411	-0.639	-0.300	-0.243
4	0.617	0.767	-0.083	0.046	-0.233	-0.109

Table 22: Correlation coefficients between sampling event and chemical concentrations at Site EM5.

Several sampling events for the tile line have been missed because of logistical reasons or no flow in the tile. Concentrations of sulfate and nitrate increased during the sampling period (R^2 = 0.573 for nitrate, and 0.821 for sulfate)(Figure 25). The correlation between sampling date and sulfate is partly due to a very high concentration of 1160 mg/L in April of 1999, although the nonparametric method tends to smooth out the effect of this value.

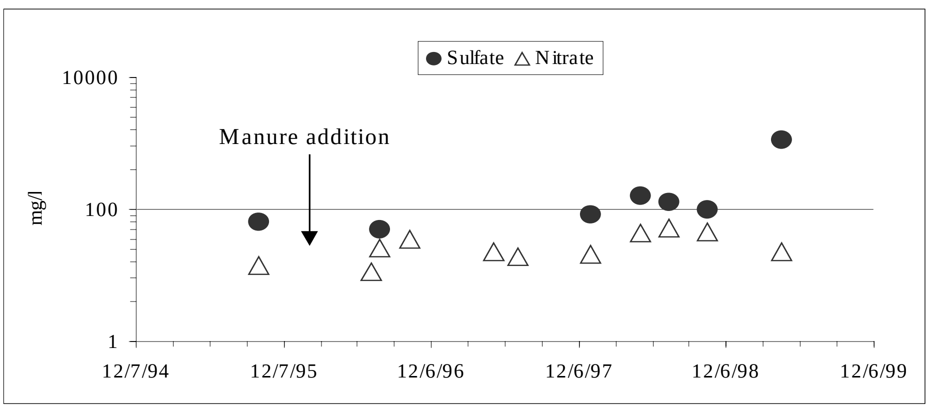

Figure 25: Concentrations of sulfate and nitrate in the perimeter tile at Site EM5.

5.3.2.6. Site EM6

Site EM6, located in Cottonwood County, consists of two 60 X 444 foot total confinement farrowing barns and a three-cell earthen basin system. Four monitoring wells surround the basins. Baseline monitoring began on December 5, 1994. Three sampling events occurred prior to addition of manure. Quarterly sampling began in spring, 1995. Figure 26 illustrates the location of manure basins and monitoring wells.

Monitoring Well 3 represented background water quality, while Well 1 represented down-gradient water quality. Using nonparametric methods, we calculated the 90% confidence tolerance limits. We observed no significant differences in concentrations of sulfate, chloride, nitrate, specific conductance, total Kjeldahl nitrogen, and ammonia. Data for Well 4 showed a negative correlation between sampling event and concentrations of nitrate and chloride, and a positive correlation between sampling event and concentrations of sulfate and specific conductance (Table 23). Well 4 is side-gradient of the manure system.

We calculated nonparametric correlation coefficients between sampling event and chemical concentration. Table 23 summarizes results of this analysis. The data reveal no significant correlations between sampling event and chemical concentrations in down-gradient wells. Ground water impacts from the manure storage system were not evident at Site EM6.

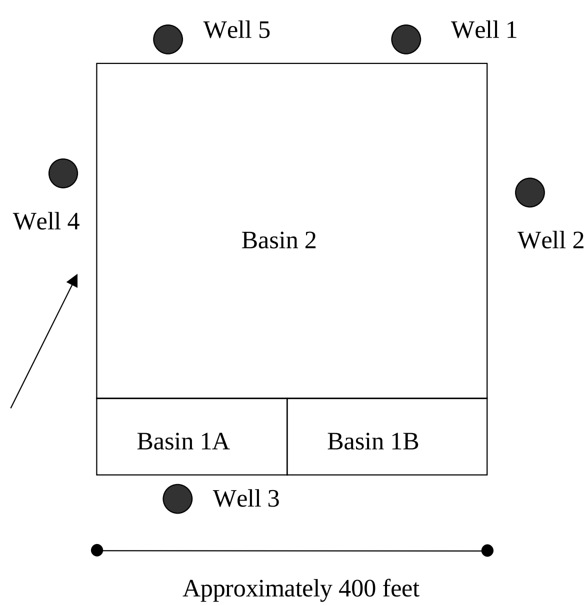

Figure 26: Location of monitoring wells, manure basins, and ground water flow direction (arrow) at site EM6.

Well	Sulfate	Chloride	Nitrate	Specific conductance	Ammonia
1	-0.317	0.117	-0.267	0.283	-0.254
2	0.090	-0.536	-0.450	0.286	-0.906
3	-0.067	0.583	-0.083	0.075	-0.424
4	0.607	-0.811	-0.955	0.865	-0.490
5	-0.214	-0.750	-0.571	-0.286	-0.631

Table 23: Correlation coefficients between sampling event and chemical concentrations at Site EM6.

5.3.2.7. Site EM7

Site EM7 is located in Renville County. The site has a two-stage earthen-lined manure storage system. Four monitoring wells surround the two basins. Baseline monitoring began on January 18, 1994. Seven sampling events occurred prior to addition of manure. Quarterly sampling began in winter, 1995. Figure 27 illustrates the location of manure basins and monitoring wells.

Well 1 is up-gradient of the basins and Well 3 is down-gradient. Using nonparametric methods, we calculated the 90 percent confidence tolerance limits. We observed no significant differences between Wells 1 and 3 in concentrations of sulfate, chloride, nitrate, specific conductance, total Kjeldahl nitrogen, and ammonia.

We calculated nonparametric correlation coefficients between sampling event and chemical concentrations (Table 24). Nitrate concentrations were positively correlated with sampling event in Well 1 (Figure 28). The source of nitrate is unclear but may be agricultural fields up-gradient of Well 1. Nitrate concentrations were not correlated with sampling event in down-gradient wells.

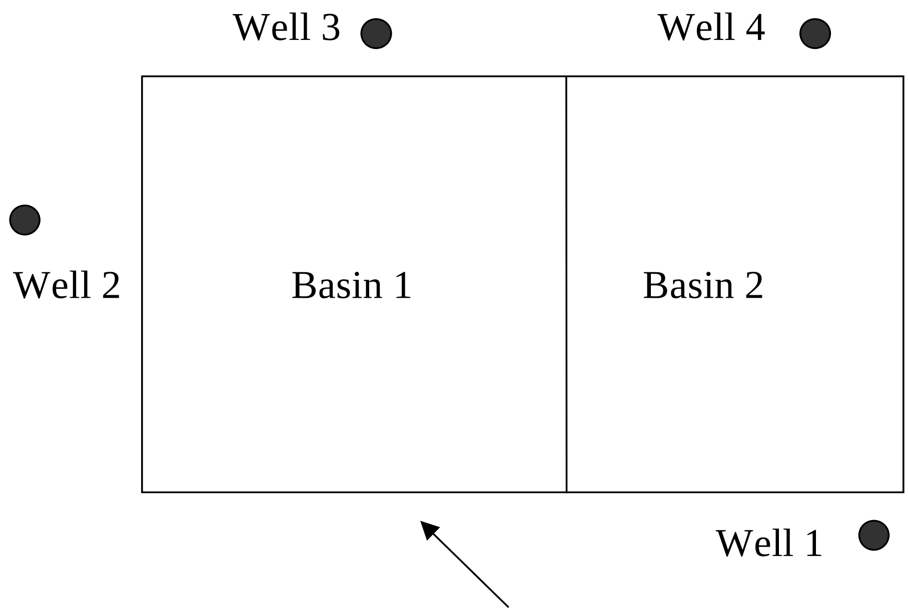

Figure 27: Location of monitoring wells, manure storage basins, and ground water flow direction (arrow) at Site EM7.

Well	**Sulfate**	**Chloride**	**Nitrate**	**Specific conductance**	**Ammonia**
1	-0.400	0.536	0.879	-0.396	-0.310
2	0.268	0.319	-0.204	-0.297	-0.210
3	-0.309	0.830	-0.006	-0.394	0.320
4	-0.504	0.533	0.368	0.375	0.093

Table 24: Correlation coefficients between sampling event and chemical concentrations at Site EM7.

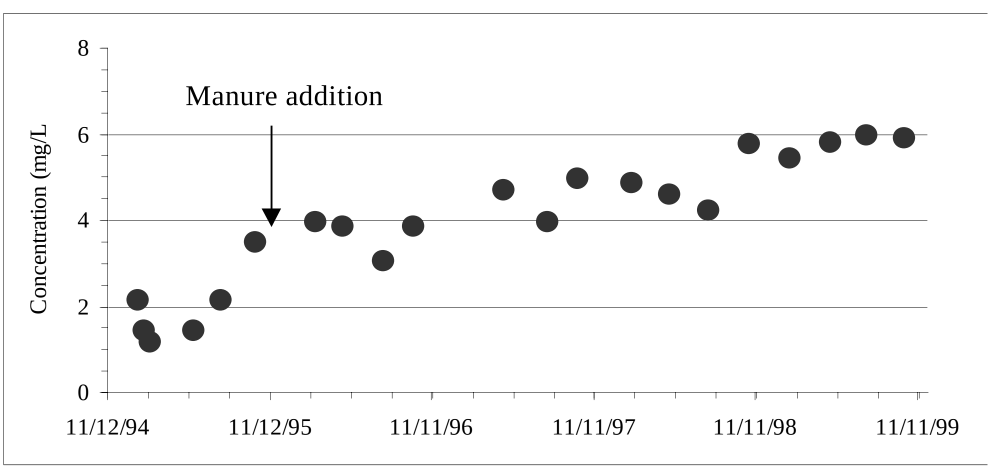

Figure 28: Nitrate concentrations and sampling date in Well 1 at Site EM7.

5.3.2.8. Site EM8

Site EM8 is located in Renville County. The facility has a two-stage earthen-lined system. Four monitoring wells surround the two basins. Two perimeter tiles surround the manure basins. Baseline monitoring began on July 26, 1994. Four sampling events occurred prior to addition of manure. Quarterly sampling began in winter, 1995. Figure 29 illustrates the location of manure basins and monitoring wells.

Well 1 is up-gradient of the basins, while Well 2 is down-gradient. Using nonparametric methods, we calculated 90 percent confidence tolerance limits. We observed no significant differences between Wells 1 and 2 in concentrations of sulfate, chloride, nitrate, specific conductance, total Kjeldahl nitrogen, and ammonia. We observed significant negative correlations between sampling event and specific conductance and concentrations of sulfate and nitrate in Wells 1 and 2 (Table 25).

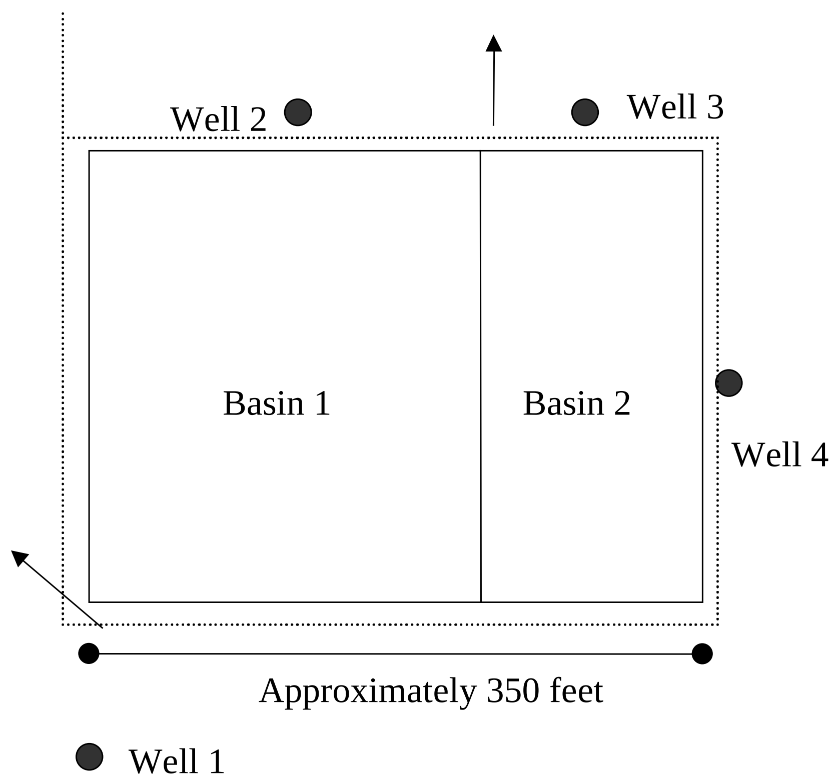

Figure 29: Location of manure storage basins, monitoring wells, and ground water flow direction (arrow) at site EM8. The dashed line illustrates the location of the tile lines.

Well	Sulfate	Chloride	Nitrate	Specific conductance	Ammonia
1	-0.874	-0.411	-0.814	-0.764	-0.472
2	-0.857	-0.466	-0.825	-0.696	0.184
3	-0.127	-0.766	-0.726	-0.468	-0.213
4	-0.438	-0.075	-0.196	-0.104	-0.489

Table 25: Correlation coefficients between sampling event and chemical concentrations at Site EM8.

Several perimeter tile samples were collected prior to addition of manure. Quarterly sampling from tile lines occurred in 1996 for nitrate, ammonia, sulfate, chloride, specific conductance, and fecal coliform bacteria. Since 1996, however, only four samples have been collected from the perimeter tiles. Consequently, there is insufficient information for assessing impacts from the basins.

5.3.2.9. Site EM9

Site EM9 is located in Renville County. The facility has a two-stage earthen-lined system. Four monitoring wells and a tile line surround the two basins. Baseline monitoring began on June 3, 1994. Four sampling events occurred prior to addition of manure. Quarterly sampling began in winter, 1995. Figure 30 illustrates the location of manure basins and monitoring wells.

Well 1 is up-gradient of the manure basins and Well 3 is down-gradient. Comparing down- and up-gradient wells, we calculated 90 percent tolerance intervals for sulfate, chloride, nitrate, specific conductance, and ammonia. No concentrations exceeded the tolerance limit, indicating that concentrations are similar in up- and down-gradient wells. Sulfate concentrations were negatively correlated with sampling event in Well 1 (R^2 = -0.622), Well 3 (R^2 = -0.765), and Well 4 (R^2 = –0.842). Concentrations of Kjeldahl nitrogen and ammonia were higher in Wells 3 and 4 than in Wells 1 and 2, but these high concentrations existed prior to addition of manure in 1995.

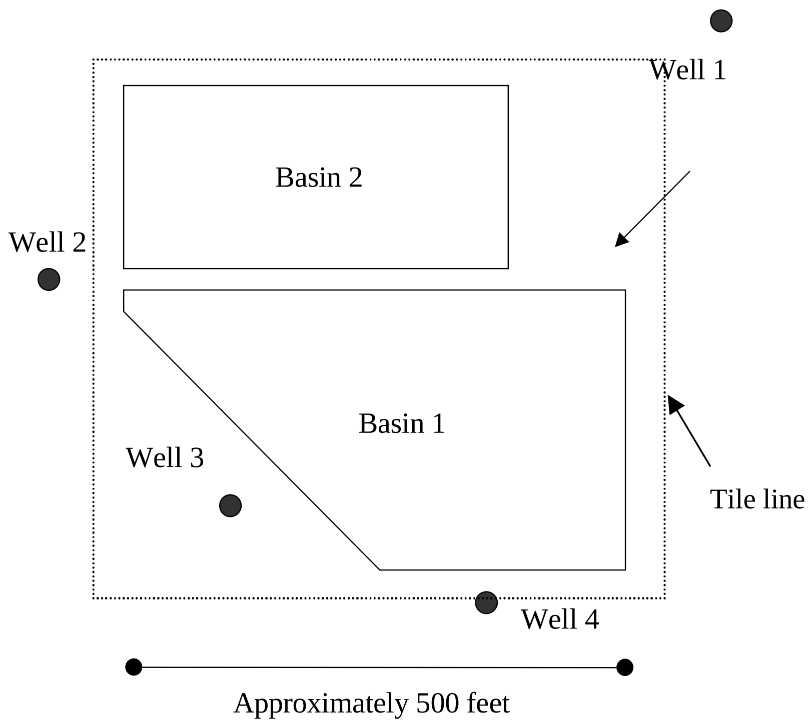

Figure 30: Location of monitoring wells, manure basins, and ground water flow (arrow) at Site EM9.

Well	Sulfate	Chloride	Nitrate	Specific conductance	Ammonia
1	-0.622	0.051	-0.389	0.384	-0.081
2	-0.394	0.193	0.210	-0.154	-0.410
3	-0.765	-0.611	-0.168	-0.082	-0.264
4	-0.842	-0.658	-0.122	0.061	-0.298

Table 26: Correlation coefficients between sampling event and chemical concentrations at Site EM9.

There were negative correlations between sampling event and concentrations of nitrate (R^2 = -0.814) and ammonia (R^2 = -0.558) in tile line samples. Sampling event was positively correlated with concentrations of Kjeldahl nitrogen (R^2 = 0.746) in tile line samples. Kjeldahl nitrogen was detected in the last five sampling events after being undetected in 1995 and 1996. The maximum concentration of Kjeldahl nitrogen was 1.10 mg/L. The median annual nitrate concentration in tile lines decreased from 16.3 in 1996 to 9.45 mg/L in 1999.

5.3.2.10. Site EM10

Site EM10 is located in Renville County. It has a two-stage earthen basin system. Four monitoring wells surround the two basins. A perimeter tile surrounds the facility and drains to an adjacent County ditch. Baseline monitoring began on July 6, 1994. Four sampling events occurred prior to addition of manure. Quarterly sampling began in spring, 1995. Figure 31 illustrates the location of manure basins and monitoring wells.

Well 1 is up-gradient of the manure basins, while Wells 3 and 4 are down-gradient. Comparing down- and up-gradient wells, we calculated 90 percent tolerance intervals for sulfate, chloride, nitrate, specific conductance, and ammonia. No concentrations exceeded the tolerance limit, indicating that concentrations are similar in up- and down-gradient wells. Upper tolerance limits were approached for chloride and specific conductance during the last sampling event, however (Figure 32).

The strongest correlations between chemical concentration and sampling event were for Well 2, which is side-gradient to the manure basins (Table 27). Concentrations of sulfate and nitrate were negatively correlated with sampling event in Well 2 (R^2 = -0.736 for sulfate and -0.884 for nitrate) (Figure 33). Sampling event was positively correlated with specific conductance (R^2 = 0.692) and chloride concentration (R^2 = 0.849) (Figure 34).

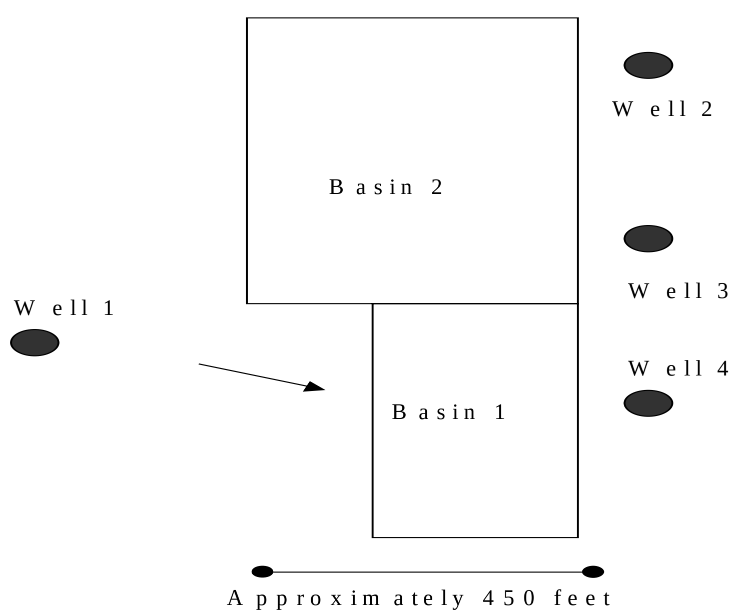

Figure 31: Location of monitoring wells, manure basins, and ground water flow direction (arrow) at Site EM10.

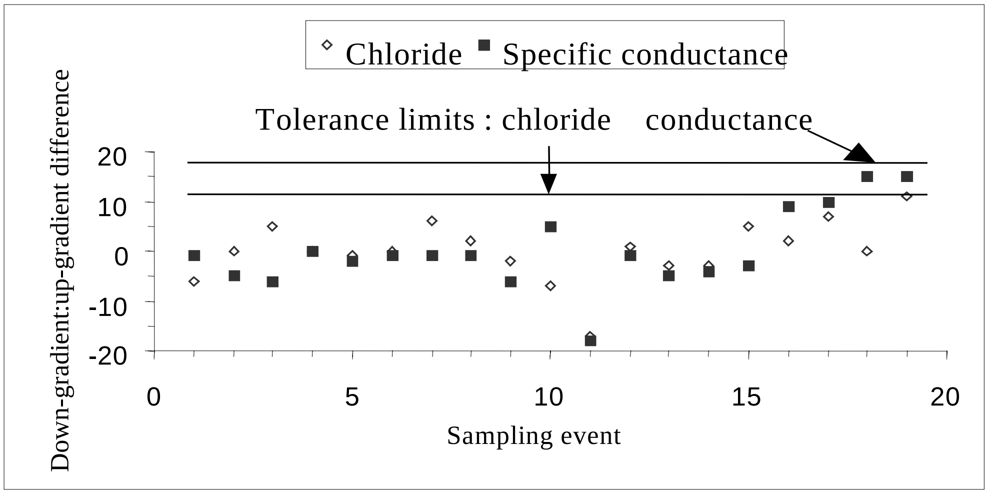

Figure 32: Tolerance limits for chloride and specific conductance at Site EM10. Well 1 is the up-gradient well and Wells 3 and 4 are the down-gradient wells.

Well	Sulfate	Chloride	Nitrate	Specific conductance	Ammonia
1	-0.654	0.606	0.209	-0.071	-0.617
2	-0.736	0.849	-0.884	0.692	-0.057
3	-0.269	0.456	0.028	0.381	-0.092
4	0.554	-0.418	-0.506	0.272	0.102

Table 27: Correlation coefficients between sampling event and chemical concentrations at Site EM10.

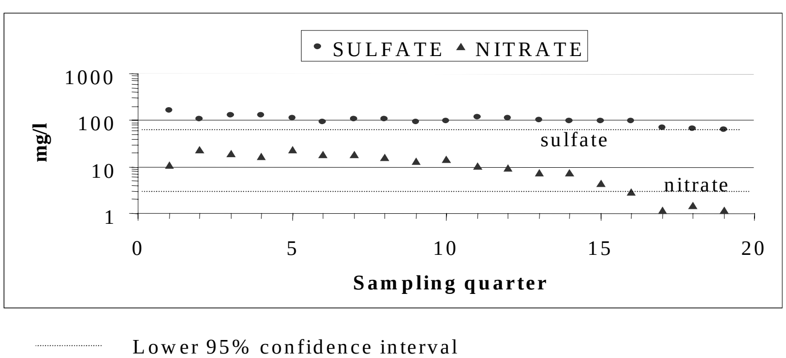

Figure 33: Distribution of sulfate and nitrate in Well 2 at Site EM10, as a function of sampling event. Lower 95% confidence intervals are used because chemical concentrations decreased with sampling event.

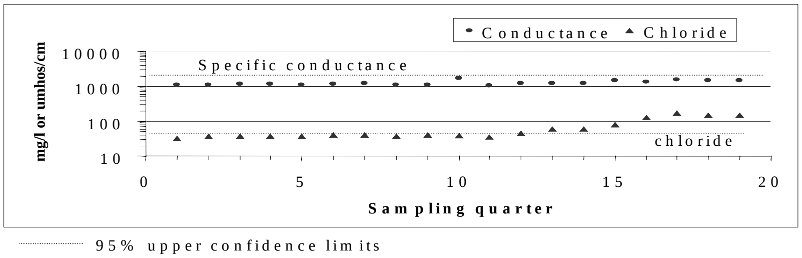

Figure 34: Distribution of chloride and specific conductance in Well 2 at Site EM10, as a function of sampling event. Upper 95% confidence intervals are used because chemical concentrations increased with sampling event.

The tile has frequently been dry, including 1997 when no samples were collected. Correlation analysis indicated positive correlations between sampling event and specific conductance (R^2 = 0.809) and concentrations of chloride (R^2 = 0.718). Concentrations were higher in 1998 compared to other years. The higher concentrations in 1998 may have been associated with the dry conditions in 1997. Sampling event was negatively correlated with concentrations of nitrate (R^2 = -0.637) and sulfate (R^2 = –0.692).

5.3.2.11. Site EM11

Site EM11 is located in Goodhue County, Minnesota. The site has one 458 X 92 foot freestall barn, one 90 X 40 foot total confinement barn, one 232 X 92 foot total confinement barn, and a two-stage earthen-lined storage system. In 1995, tile lines were installed around the cells of the manure basins. Four background samples were collected prior to addition of manure to the earthen basin in October 1995. Samples have been collected quarterly since 1996. Figure 35 illustrates the location of the tile lines in relation to the manure basins.

Flow rate and concentrations of sulfate, nitrate, and chloride differed between the four tile lines (Figure 36). The south tile had more flow and high concentrations of chloride and nitrate compared to other tiles, while the east tile had low concentrations of chloride and nitrate. Reasons for the differences are unclear. Chemical concentrations were not correlated with flow rate.

Correlation analysis using nonparametric methods indicate a positive correlation between sampling event and specific conductivity in all four-tile lines (Table 28). We observed negative correlations between sampling event and nitrate concentrations in the north, east, and west tiles, and for chloride in the north and east tiles. There were positive correlations between sampling event and concentrations of sulfate in the north and west tiles. Typically, increasing concentrations of chloride, increasing values for specific conductance, and decreasing concentrations of nitrate are evidence of impacts from manure storage systems. Other indicators may include increasing concentrations of Kjeldahl nitrogen, and phosphorus, and decreasing concentrations of sulfate. The chemistry of water entering the tile lines may provide evidence of a transition in water quality. Additional sampling of redox parameters, such as redox potential, dissolved oxygen, and reduced iron, may provide additional information about the redox status of water entering the tile lines.

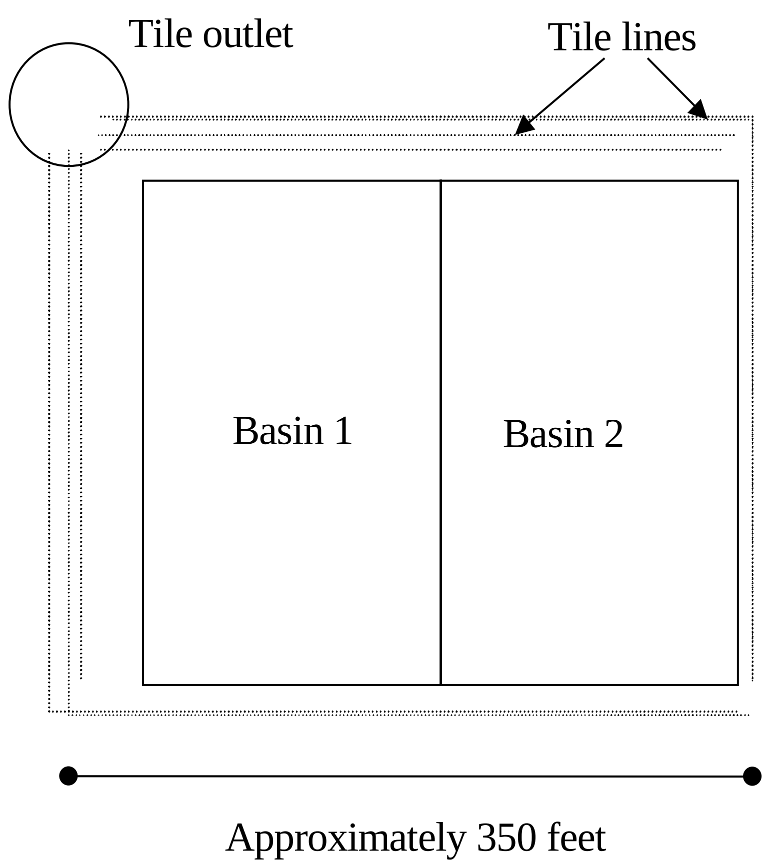

Figure 35: Location of manure basins, tile lines, and tile outlet at Site EM11.

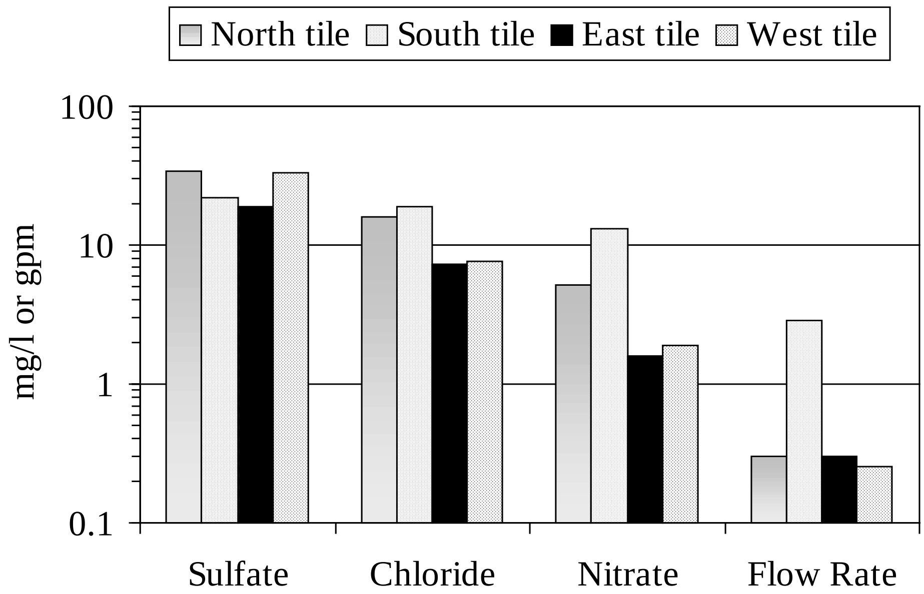

Figure 36: Flow rate and concentrations of sulfate, chloride, and nitrate in tile lines at Site EM11.

Parameter	Tile 1	Tile 2	Tile 3	Tile 4
Sulfate	0.579	0.200	0.407	0.832
Chloride	-0.729	0.093	-0.550	-0.101
Nitrate	-0.738	-0.404	-0.685	-0.709
Dissolved oxygen	-0.074	-0.058	-0.475	-0.174
Specific conductance	0.889	0.926	0.906	0.970
Phosphorus	-0.390	-0.308	-0.448	-0.567
Kjeldahl nitrogen	0.718	-0.188	-0.103	0.110
Correlations with flow	Phosphorus (+)	Kjeldahl nitrogen (-)	None	Dissolved oxygen (-)

Table 28: Correlation coefficients between sampling event and chemical concentrations at Site EM11.

5.2.3.12. Site EM15

Site EM15 is located in Dodge County, Minnesota. The hog-producing facility contains one 71 X 312 foot total confinement barn and a two-stage earthen-lined manure system that holds manure for approximately 8000 animal units. The system was constructed in late 1994. Figure 37 illustrates the location of the perimeter tile and manure basins at the site. Several background water quality samples were collected prior to addition of manure in early 1995.

Sampling parameters included sulfate, chloride, nitrate, ammonia, Kjeldahl nitrogen, and occasionally phosphorus.

Concentrations of sulfate, Kjeldahl nitrogen, and ammonia were positively correlated with sampling event in the perimeter tile (R^2 = 0.556 for sulfate, 0.645 for Kjeldahl nitrogen, and 0.753 for ammonia). Figures 38 and 39 illustrate concentrations of sulfate, chloride, ammonia and Kjeldahl nitrogen in tile lines since 1994. We observed no effect of season or year of sampling ($p > 0.100$) on the chemical concentrations. Concentrations of chloride, Kjeldahl nitrogen, and ammonia were greater than concentrations prior to addition of manure ($p < 0.05$).

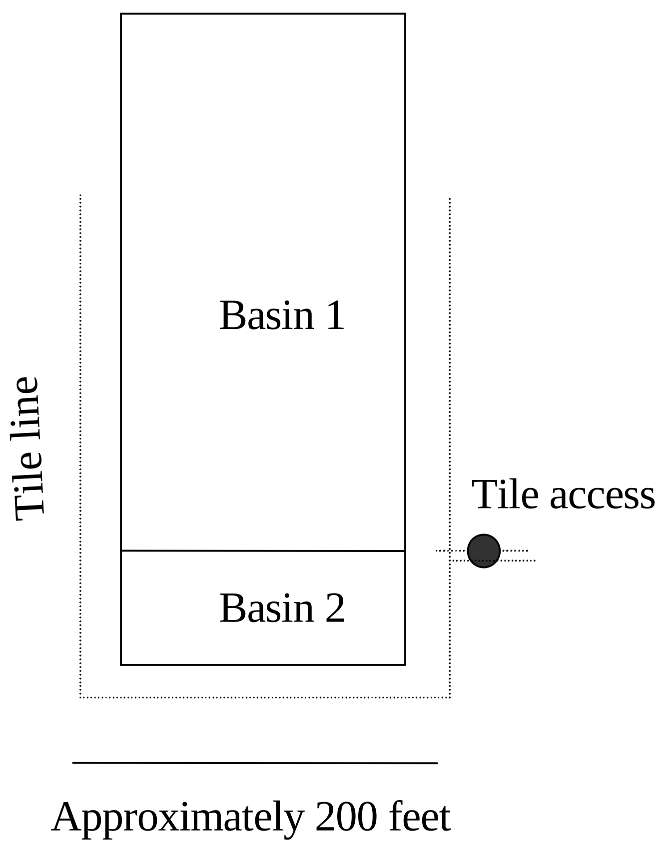

Figure 37: Location of manure storage basins and perimeter tile at Site EM15.

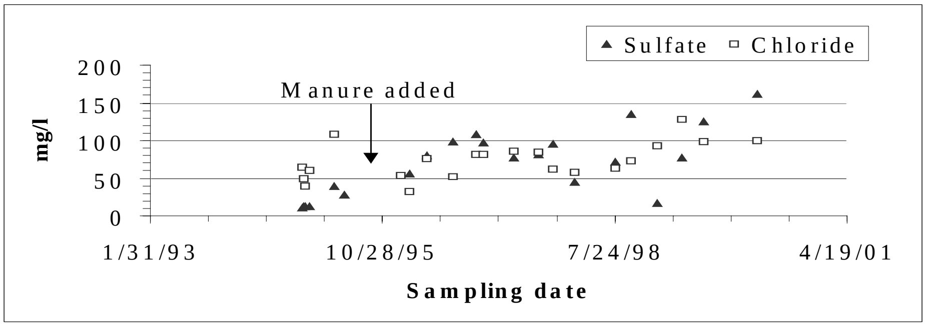

Figure 38: Concentrations of chloride and sulfate in the perimeter tile at Site EM15.

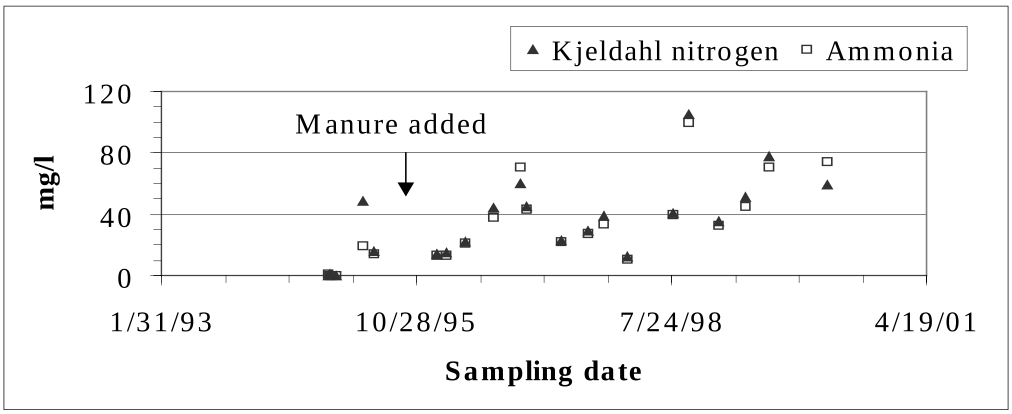

Figure 39: Concentrations of Kjeldahl nitrogen and ammonia in the perimeter tile at Site EM15.

5.3.2.13. Site EM16

Site EM16 is located in Waseca County. The hog-producing facility includes five 41 X 225 foot total confinement barns and a two-stage, earthen-lined manure storage system. There are approximately 4800 animal units. The system was constructed in 1996. Background sampling, prior to the addition of manure, occurred on three occasions in 1996. Quarterly sampling began in 1997 following the first addition of manure. The site is surrounded by a tile drain. Flow within the tile is split into two, with drainage from the northern and eastern part of the system in one of the tiles and drainage from the southern and western portions of the system in the other tile. Figure 40 illustrates the location of tile lines relative to the manure basins.

Concentrations of nitrate and sulfate have decreased in both tile lines since the addition of manure (Figure 41). There were no correlations between flow rate in the tile lines and concentrations of sulfate or nitrate. The relationships involving nitrate and sulfate reflect a change in the redox status of ground water adjacent to the manure storage systems. Despite this, there is no evidence of increased concentration of other chemicals, such as chloride, phosphorus, ammonia, and Kjeldahl nitrogen, which typically provide an indication of seepage from a manure storage system.

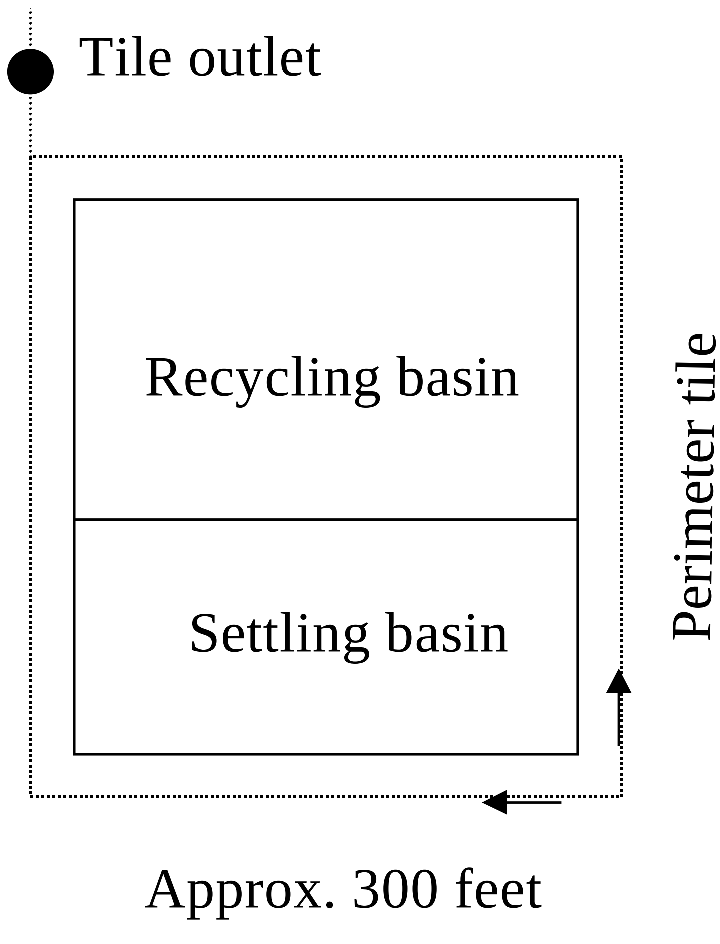

Figure 40: Location of manure storage basins and tile lies at Site EM16.

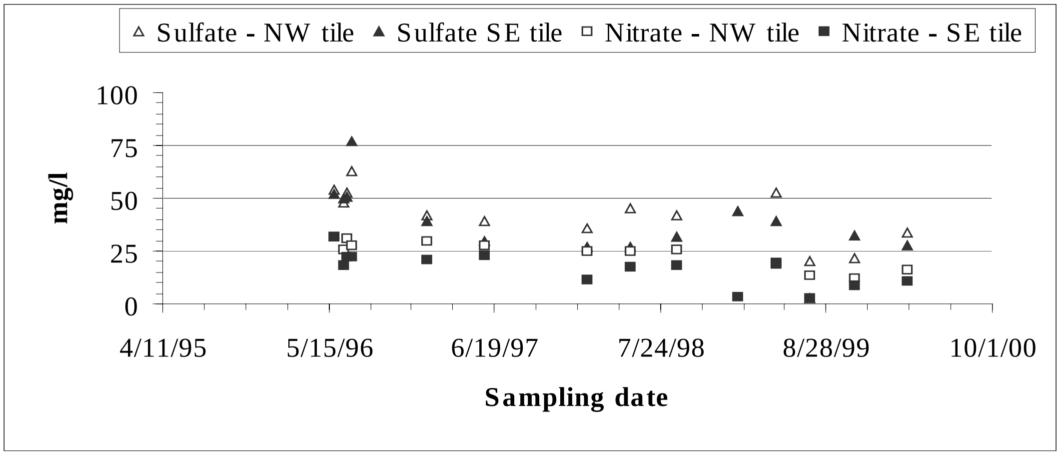

Figure 41: Concentrations of nitrate and sulfate in tile lines at Site EM16, as a function of sampling date.

5.3.2.14. Summary

Table 29 summarizes results of analyses at sites with permanent monitoring networks. An impact means there is statistical evidence that concentrations of one or more indicator chemicals is greater in down-gradient wells than in up-gradient wells. A correlation means that the concentration of an indicator (see Glossary for definition) was significantly correlated with sampling event in down-gradient but not up-gradient wells. Statistical methods were described in Section 2.4. Indicators are used to identify leaching of liquid manure through manure basins and into ground water.

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. We did not conduct rigorous trend analysis of the data because it often takes more than five years for trends 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, the monitoring networks were not designed for rigorous statistical analysis. Factors such as seasonality and spatial correlation are difficult to assess. Fourth, there may be other sources of chemicals such as chloride and nitrate. Sources include agricultural fields, abandoned feedlots, and septic systems. These were not identified during the study. Fifth, 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. Finally, there were usually no more than two significant correlations between sampling event and chemical concentrations. These results do not provide conclusive evidence of impacts from manure storage, but provide evidence to support continued monitoring.

Table 29 indicates positive correlations between sampling event and one or more indicator chemicals at seven sites. Negative correlations or no correlation were evident at four sites. Data at the remaining two sites were inconclusive. Impacts were observed only at Site EM3, where concentrations of one or more indicator were significantly higher in down-gradient wells since the addition of manure.

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

5.3.3. Investigations of Leachate Collection Systems

Since 1998, we have monitored three sites that have leachate collection systems (lysimeters) installed beneath earthen-lined manure storage systems. Figure 42 illustrates the location of these sites. 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 30 summarizes seepage water quality at the three sites between 1998 and 2000. Data was collected at each of these sites prior to 1998. Results of this sampling are discussed in other documents (Ruhl, 1999; Clanton, document in preparation).

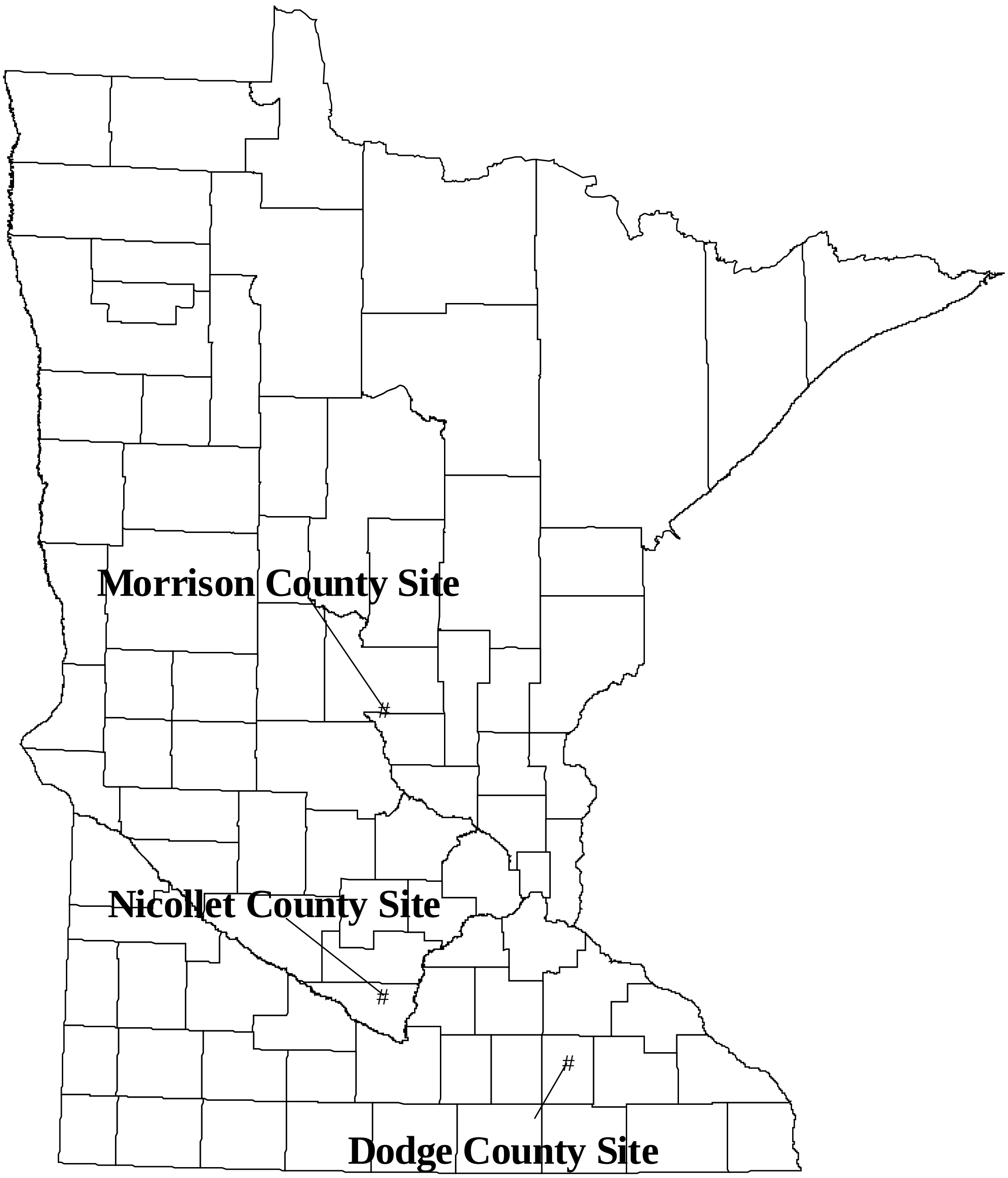

Figure 42: Location of sites with lysimeters.

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 30: 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 bottom and sidewall of the basin. This reflects 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. Concentrations of reduced nitrogen in samples from the sidewall increased during the sampling period. This was the result of very high concentrations of reduced nitrogen in samples collected in 2000. Additional data is needed to determine if the apparent trend is real or 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. These results are in agreement with those of Wall (personal communication), who observed seepage rates of 102 gallons per day from sidewalls and 5 gallons per day from the basin bottom during the first three years of the study. 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. Wall (personal communication) observed total nitrogen, phosphorus, potassium, sulfate, sodium, and chloride concentrations, as a percentage of the concentrations in manure, of 0.2, 0.03, 1.0, 5, 25, and 44 during the first three years of the study. Overall results from all years of sampling are in preparation by Chuck Clanton of the University of Minnesota.

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 for all chemicals except nitrogen. Nitrogen is at higher concentration in leachate from the agricultural fields, resulting in higher concentrations in tile lines compared to bottom and sidewall samples. We observed positive correlations between sampling event and concentrations of reduced nitrogen in bottom and sidewall samples (R^2 = 0.622 and 0.838, respectively). Despite these correlations, concentrations of total nitrogen remained 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. More rigorous analysis of the water quality data is needed, particularly with respect to rates of leaching through the basin bottoms and sidewalls. An important component of continued monitoring at these sites is determination of seepage rates, since the development of a plume down-gradient of a manure basin is largely a function of the seepage rate.

6. Manure Storage Basins Constructed with Concrete Basins

6.1. Abstract

We sampled two sites having concrete-lined storage systems older than five years. Two basins existed at one of the sites. Plumes were evident at each site, but did not extend more than about 100 feet from the manure basin. Elevated concentrations of nitrogen and chloride characterized the plumes, but concentrations were low compared to other types of manure storage systems.

Monitoring networks were established at four sites with newly constructed concrete-lined manure basins. Each site had no prior history of manure storage. Monitoring at these sites did not begin until 1998. Consequently, there is limited data to assess ground water impacts from the manure basins.

6.2. Introduction

In Minnesota, poured concrete-lined basins are most commonly used to store manure from swine. They are more expensive to install than earthen-lined systems. Concrete-lined systems typically have a permeability of 10^{-8} cm/s or less. Like other systems, an organic seal forms at the base of the concrete liner. Properly-constructed 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. Concrete liners can have cracks and joints prior to addition of manure, and there may be foundation shifts associated with freezing and thawing.

There is very little information regarding ground water impacts from concrete-lined systems. Bickford (1983) studied a manure storage system consisting of a concrete-lined floor and earthen sidewalls. Chloride and nitrate concentrations immediately down-gradient of the basin were three to six times greater than background concentrations. There were spikes in nitrate and chloride concentrations. Cracking and erosion of the earthen sidewalls was observed and this may have led to the concentration spikes. Ground water impacts were observed up to 200 feet from the basin, but the greatest impacts were within 60 feet of the basin. Ammonia concentrations exceeded 1 mg/L immediately down-gradient of the basin, but concentrations were not elevated in any other well. Swoden and Hore (1976) observed no significant impacts to ground water beneath a 30-year old concrete-lined system in Ottawa, Canada. Meyer (1998) observed no significant ground water quality impacts down-gradient of a large hog facility in South Dakota.

6.3. Monitoring in Minnesota

There are few studies of concrete-lined systems in Minnesota. We conducted sampling at older facilities using temporary wells. We are also conducting long-term monitoring at feedlots with no prior history of manure storage and where new concrete-lined systems have been built. At each site, the concrete basin was located beneath a hog barn.

6.3.1. Sampling of Temporary Wells

Monitoring of sites with concrete liners consisted of drilling temporary wells at sites with manure storage systems older than five years. We selected two sites for sampling. Table 31 summarizes characteristics of these sites. Figure 42 illustrates the location of these sites. Both sites are located on coarse-textured soils. This represents a situation where ground water is most sensitive to contamination from liquid manure leachate.

Site	Animal	Animal units	Approx. Years of operation	Depth to water (ft)[1]	Soil
C1[2]	Hogs	815	10	15 to 20	Coarse sand and gravel
C2	Hogs	500	10	15 to 20	Coarse sand and gravel

[1] These depths represent the range of depths encountered during drilling of temporary wells.
[2] Site C1 has two concrete-lined basins.

Table 31: Sampling sites with concrete-lined manure storage systems.

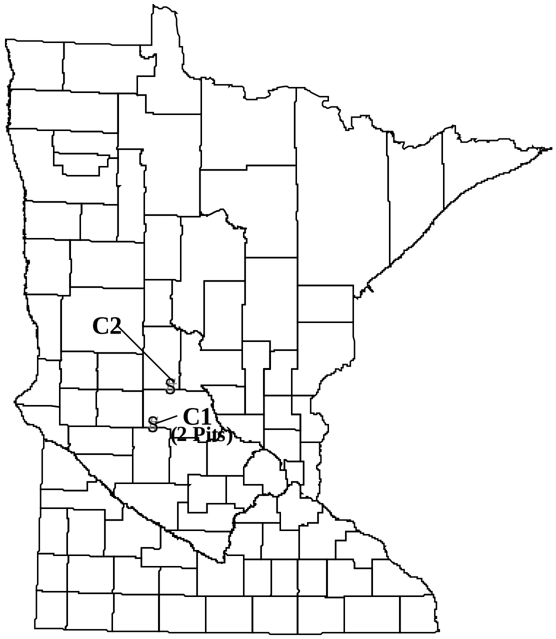

Figure 43: Location of sites with concrete-lined manure storage systems.

6.3.1.1. Site C1

Figure 43 illustrates the location of temporary wells at Site C1. Two concrete-lined basins exist at the site. Ground water flow is to the north-northwest. Table 32 summarizes water quality data for each of the wells.

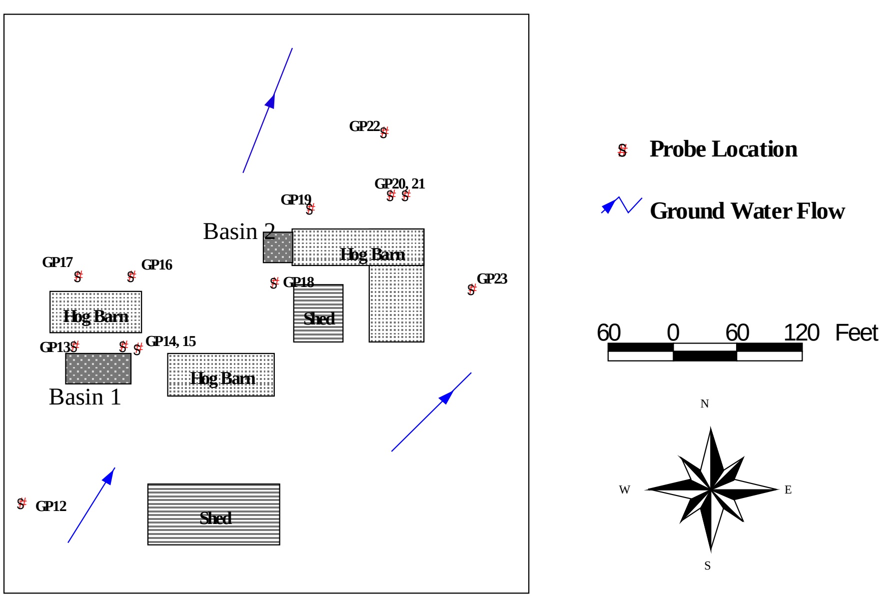

Figure 44: Location of temporary wells and ground water flow direction at Site C1.

Wells 13, 14, and 15 were the down-gradient wells closest to Basin 1. These wells showed negligible impacts from the manure basin, except for a somewhat lower dissolved oxygen concentration (6.43 mg/L) and a higher nitrate concentration (50.6 mg/L) in Well 13 compared to the up-gradient well (Well 12 - 12.2 mg/L of dissolved oxygen and 37.4 mg/L of nitrate). The median rank in down-gradient wells was 3.1, compared to a rank of 1.9 in Well 12, providing some evidence of ground water impacts from the manure basin. Differences in chemical concentrations are difficult to discern, however. Assuming Well 13 is impacted and Wells 16 and 17 are not, plume length is about 50 feet. Well 16, located down-gradient of Basin 1, had very high iron concentrations. The Eh in this well was 296 mV and nitrate was present at a concentration of 25.1 mg/L. The iron concentration is an anomaly and may represent a sampling error.

At Basin 2, Well 18, located up-gradient of Basin 2, had an overall rank of 4.5. This was similar to ranks in down-gradient wells. Well 18, however, is located in an area where animals are active. Comparing concentrations of nitrate in Well 19 (down-gradient) and Well 12, we detect an increase of about 15 mg/L in the down-gradient well.

In Well 22, located further down-gradient of Basin 2, the nitrate concentration is about 7 mg/L greater than in Well 12. Chloride may provide the best evidence for delineating a plume. Chloride concentrations in Well 19 were 40.5 mg/L, compared to 29.4 mg/L in Well 12. In Well 22, chloride concentrations were less than in Well 12. Assuming a plume extends between Wells 19 and 22, plume length would be about 125 feet.

6.3.1.2. Site C2

Figure 44 illustrates the location of temporary wells at Site C2. Ground water flow is to the east. Table 33 summarizes water quality data for each of the wells. The highest rank was in Well 6, located down-gradient of the manure basin. The concentration of nitrate in Well 6 was 70.4 mg/L, compared to 20.2 mg/L in Well 3, located up-gradient of the manure basin. Concentrations of organic carbon (142 mg/L), potassium (179 mg/L), and phosphorus (14.4 mg/L) were also higher in Well 6 than in Well 3 (31.1, 38.2, and 3.93 mg/L, respectively). We therefore assumed a plume extended from the manure basin for about 100 feet. As with the two basins at Site C1, concentrations of chemicals in the plume were relatively low, however, compared to other types of manure storage systems.

Well location	Well ID	Basin	Ammonia	Chloride	Dissolved oxygen	Eh	Iron	Nitrate
			mg/L	mg/L	mg/L	mV	mg/L	mg/L
Basin 1								
Up	12	1	0.030	29.4	12.2	302	< 0.0031	37.4
Down	13	1	0.060	24.6	6.43	291	< 0.0031	50.6
Down	14	1	0.070	29.6	11.1	290	< 0.0031	49.6
Down	15	1	0.070	34.6	8.92	309	< 0.0031	30.8
Down	16	1	0.070	14.5	11.7	296	5.72	25.1
Down	17	1	0.060	28.7	9.86	306	< 0.0031	43.7
Basin 2								
Up	18	2	0.07	99.3	11.19	302	0.0044	50.2
Down	19	2	0.06	40.5	9.34	294	0.013	52.2
Down	20	2	0.04	25.8	8.44	285	< 0.0030	39.1
Down	21	2	0.07	39.3	2.60	300	< 0.0030	36.7
Down	22	2	0.08	19.1	5.81	293	0.0062	44.2
Side	23	2	0.05	31.8	11.05	291	0.0034	32.4

Well location	Well ID	Basin	Potassium	Sodium	Total Kjeldahl nitrogen	Total Organic carbon	Total phos-phorus	Average Rank
			mg/L	mg/L	mg/L	mg/L	mg/L	
Basin 1								
Up	12	1	2.0	7.9	0.400	1.3	0.020	1.9
Down	13	1	3.18	13.7	0.310	2.30	< 0.020	3.1
Down	14	1	2.40	6.64	0.360	1.60	< 0.020	3.0
Down	15	1	2.63	8.21	0.400	1.80	< 0.020	3.3
Down	16	1	4.09	7.02	0.390	1.80	0.163	3.7
Down	17	1	4.50	10.6	0.37	1.60	< 0.020	2.8
Basin 2								
Up	18	2	60.8	16.8	0.500	2.4	0.020	4.5
Down	19	2	41.6	11.6	0.520	2.8	0.074	4.5
Down	20	2	103	16.2	0.690	3.7	2.40	4.4
Down	21	2	2.80	6.74	0.260	1.4	0.020	2.9
Down	22	2	56.0	21.1	1.19	7.5	0.049	4.6
Side	23	2	7.88	8.18	0.280	1.5	0.030	4.2

[1] Wells were screened within two feet of the water table, except Wells 15 and 21, which were screened 7 feet below the water table.

Table 32: Summary of water quality at Site C1. Well locations are hydraulically relative to the animal containment area, where Up = up-gradient, Side = side-gradient, and Down = down-gradient.

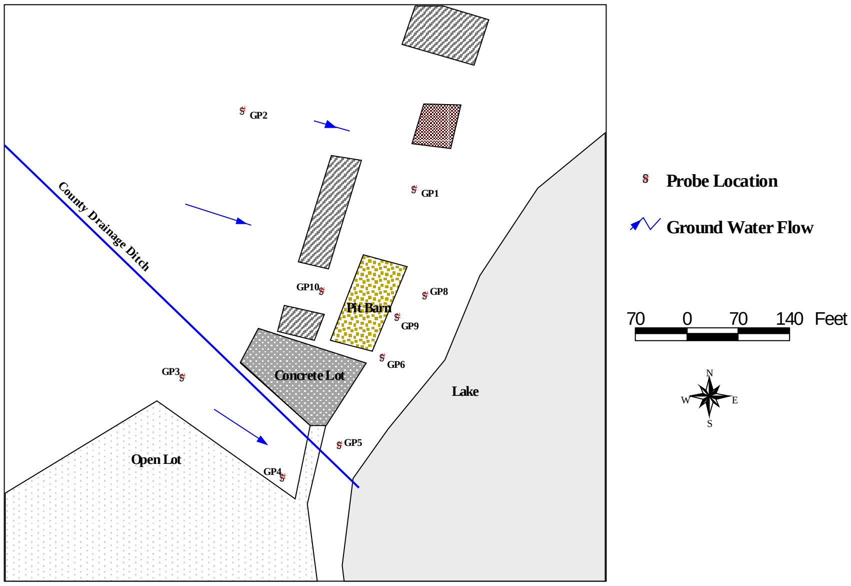

Figure 45: Location of wells and ground water flow direction at Site C2.

Well location	Well ID	Ammonia	Chloride	Eh	Iron	Nitrate	Phosphorus
		mg/L	mg/L	mV	mg/L	mg/L	mg/L
Up	3	0.63	113	278	0.178	20.2	3.93
Up	10	3.12	15.0	8	0.117	< 0.0020	7.48
Side	1	1.25	99.6	268	0.006	0.17	0.44
Side	2	1.55	20.1	214	0.980	2.81	13.2
Side	4	2.48	43.7	272	0.442	0.29	9.43
Side	5	3.59	10.8	121	9.06	0.11	3.23
Down	6	1.54	64.4	-	0.152	70.4	14.4
Down	8	2.29	71.0	-	0.481	0.22	8.71
Down	9	2.32	25.0	10	1.79	0.030	6.57
Well location	**Well ID**	**Potassium**	**Sodium**	**Sulfate-S**	**Total Kjeldahl nitrogen**	**Total Organic carbon**	**Average Rank**
		mg/L	**mg/L**	**mg/L**	**mg/L**	**mg/L**	
Up	3	38.2	17.5	25.8	-	31.1	4.2
Up	10	38.2	21.6	14.5	6.17	5.90	5.0
Side	1	5.12	10.2	44.8	3.58	20.5	4.1
Side	2	3.27	11.4	29.9	5.47	19.5	3.8
Side	4	32.8	9.18	17.6	18.5	88.9	4.9
Side	5	4.87	7.30	1.21	8.89	23.4	5.6
Down	6	179	18.6	31.2	21.2	142	4.7
Down	8	7.31	15.2	110	7.72	14.2	4.7
Down	9	8.06	34.1	51.9	5.77	17.2	4.9

Table 33: Summary of water quality at Site C2. Well locations are hydraulically relative to the animal containment area, where Up = up-gradient, Side = side-gradient, and Down = down-gradient.

6.3.1.3. Summary

Table 34 illustrates excess chemical concentrations at each of the sites with concrete liners. Estimates of plume length are included in Table 34. 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.

Site	Approximate plume length (ft)	Excess down-gradient concentration (mg/L)					
		Ammonia	Total Kjeldahl nitrogen	Phosphorus	Total organic carbon	Potassium	Nitrate
C1: basin 1	50	0.04	0.00	0.14	1.0	2.5	13.2
C1: basin 2	125	0.01	0.69	2.4	7.0	39.5	2.0
C2	100	-0.80	15.0	6.9	136	141	50.2

Table 34: Approximate plume lengths and excess chemical concentrations at sites with concrete-lined systems.

6.3.2. Long-term Monitoring at Sites with Newly Constructed Concrete Liners

Permanent monitoring networks exist at four sites with newly constructed concrete-lined manure storage systems. Three of the sites have tile lines surrounding the manure storage system, while the fourth site has four monitoring wells. Each site had no previous history of manure storage. 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. Figure 46 illustrates the location of the sites. Table 35 summarizes the characteristics of each site. There was insufficient data from Sites CM1 and CM2 for analysis. We therefore discuss only Sites CM3 and CM4.

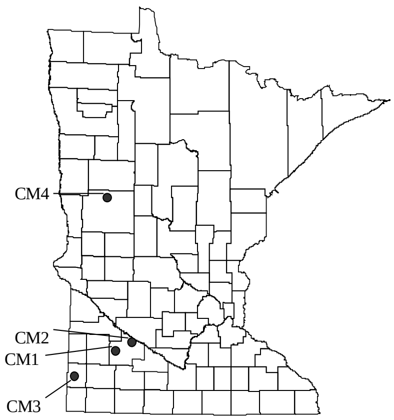

Figure 46: Location of sites having concrete-lined manure storage basins and permanent monitoring networks.

Site	Approx. Date Manure Added	Livestock	Wells	Tile lines
CM1	8/97	Hogs		X
CM2	8/97	Hogs		X
CM3	8/97	Hogs		X
CM4	Fall, 1997	Hogs	X	

Table 35: Summary information for sites having concrete-lined manure basins and permanent monitoring networks.

6.3.2.1. Site CM3

Site CM3 is located in Renville County. The facility includes a two-stage, concrete-lined system. The basins were constructed in 1997. Background sampling, prior to the addition of manure, occurred on five occasions in 1997. Quarterly sampling began in 1998 following the first addition of manure. The site is surrounded by four tile lines.

Nonparametric tests revealed significant differences in concentrations of chloride and specific conductance between the four tile lines. Concentrations of chloride were highest in Tile 1 and 4, and lowest in Tile 3. Specific conductance was highest in Tiles 1 and 2, and lowest in Tile 3. There were no differences between tile lines in concentrations of other chemicals. Correlation analysis revealed a negative correlation between sampling event and chloride concentrations in Tiles 2 and 4 (R^2 = -0.725 for Tile 2 and –0.695 for Tile 4).

Each of the four tile lines has consistently had high concentrations of coliform bacteria. Median concentrations were 50 colony forming units per 100 ml (CFU/100-mL) in Tiles 1, 2, and 4, and 88.5 CFU/100-mL in Tile 3. Concentrations were as high as 1900 CFU/100-mL. Concentrations were high prior to construction of the basin, however, and the source of the bacteria is unclear.

6.3.2.2. Site CM4

Figure 47 illustrates the location of Site CM4. The site had no previous history of livestock management and was in corn and soybean production prior to construction of the basin. Soils are coarse-textured and the depth to water is about 20 feet. The manure is collected in a concrete basin beneath the hog barn.

MPCA installed four permanent wells on June 15-16, 1998. All wells are screened at the water table. Figure 47 illustrates well locations. In autumn, 1998, a hog barn was constructed at the site. Hogs were brought to the site in February of 1999. Sampling occurred on five occasions prior to arrival of the hogs. Quarterly sampling occurred in 1999 and 2000. Sample methods are similar to those described earlier in the report. Sample parameters included major cations and anions, dissolved and total organic carbon, ammonia-nitrogen, total Kjeldahl nitrogen, and field parameters.

Initial sampling shows yearly differences in concentrations of nitrogen in MW4, located immediately down-gradient of the concrete basin. Because of these yearly differences, we cannot conduct trend analysis on the data. Additional sampling is required.

7. Manure Storage Basins Constructed with Flexible Membrane Liners

7.1. Abstract

Quarterly sampling occurred since 1998 at a dairy feedlot with an earthen basin having a geosynthetic, bentonite clay liner. The site was previously operated as an open feedlot. In just four years since construction of the manure basin, total nitrogen concentrations beneath the feedlot decreased 55 percent. Decreases in ammonia concentration account for most of the change in total nitrogen concentrations. Concentrations of phosphorus and organic carbon also decreased since construction of the basin. Changes in water quality are probably associated with

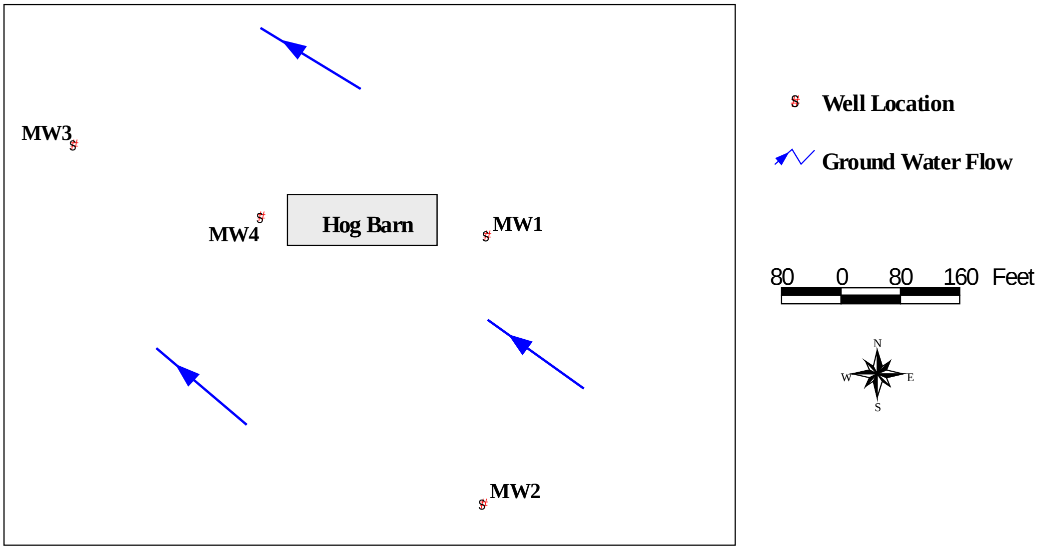

Figure 47: Location of monitoring wells at Site CM4. Manure is collected in a concrete basin beneath the hog barn.

removal of the open feedlot and increased infiltration through a grass filter strip on the site. Long-term monitoring is required to evaluate water quality associated with the new manure basin.

7.2. Introduction

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, provided they maintain their integrity (e.g. are not punctured or seams do not come loose). These materials vary considerably in their performance and durability. Little information exists on the long-term effectiveness of these materials in minimizing seepage from manure storage systems, although similar materials are widely used in landfills.

7.3. Monitoring in Minnesota

We are monitoring one site that has a geosynthetic liner. The site is the same location as Site O3 (see Section 3.3.3; Figures 1 and 4) and is a dairy farm with approximately 80 head of cattle. Prior to 1997, the site was an open feedlot. In 1997, an earthen manure storage basin with a geosynthetic, bentonite clay liner was installed. The liner was covered with one foot of native soil. A grass filter strip was constructed where the open lot had existed.

Three, two-inch diameter monitoring wells were installed on October 13-14, 1997. Wells were drilled using a hollow stem auger. Wells consist of threaded PVC pipe with a five foot, 0.010-inch slot screen completed approximately halfway across the water table. Soil samples for textural analysis were collected at five-foot intervals with a split spoon sampler. We developed the wells and surveyed the top of the inner and outer casings to an accuracy of 0.1 foot. Water levels measured on October 14 were used to develop a ground water flow map. We drilled three additional wells between October 14 and October 29, 1997, and two wells on November 24, 1997. All wells are screened at the water table. Figure 48 displays locations of the wells.

Samples for laboratory analysis have been collected quarterly since winter of 1998. Samples for laboratory analysis include major cations and anions, ammonia-nitrogen, Kjeldahl-nitrogen, total organic carbon, dissolved organic carbon, and fecal coliform bacteria. Samples were stored at 4^{o}C until delivered to the laboratory within appropriate holding times.

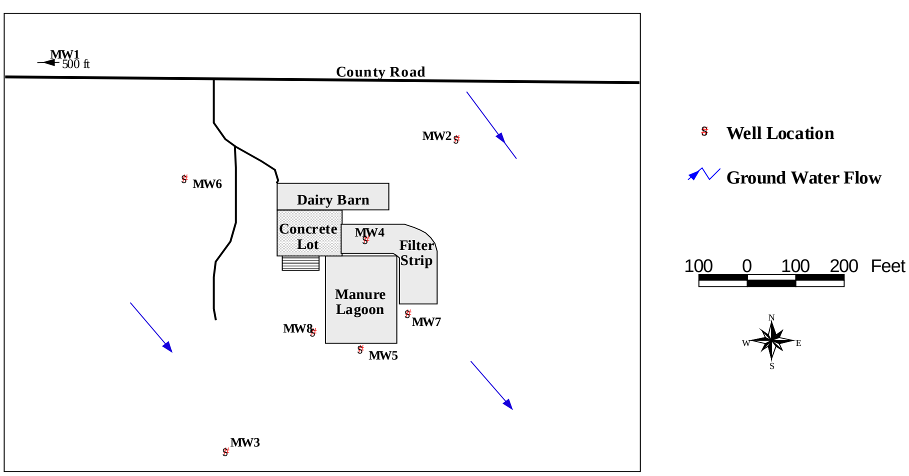

Figure 48: Location of monitoring wells and ground water flow at the site with a geosynthetic liner. Note that wells shown in Figure 48 represent permanent wells drilled after our initial investigation with temporary wells. The well locations in Figure 4 therefore differ from those shown in Figure 48.

Total nitrogen concentrations in Well MW4 decreased by about 55 percent since the manure storage system was installed (Figure 49). MW4 was completed in the former open lot. Water quality in this well thus represents water quality directly beneath the former open lot. There is no longer animal activity in this area. 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 49), while concentrations of potassium, chloride, calcium, magnesium, sulfate, bicarbonate, and sodium have not changed. Manganese concentrations decreased with time, indicating a change in the oxidation-reduction status beneath the feedlot. The rapid decrease in organic carbon concentrations suggests biological activity, which would lead to reducing conditions within the aquifer. The filter strip, however, collects storm water runoff. The storm water subsequently infiltrates the soil, percolates to ground water, and brings oxygenated water to the aquifer. Dissolved oxygen concentrations have fluctuated but remained between 2 and 6 mg/L, indicating the presence of aerobic conditions.

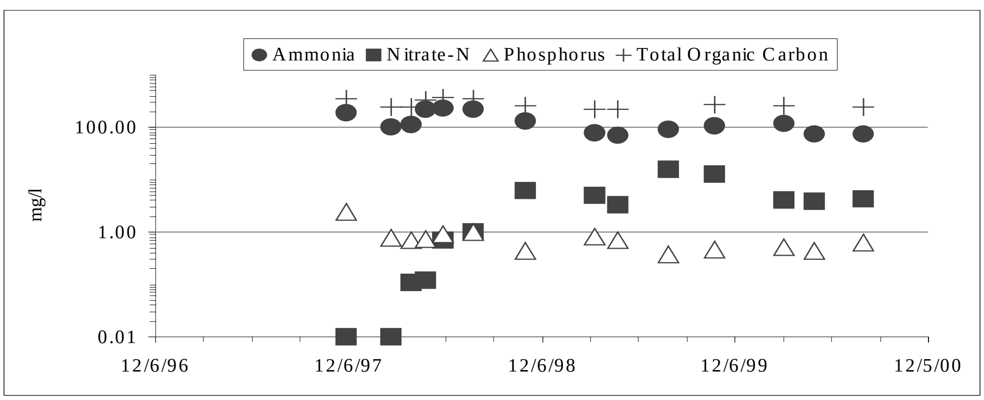

Figure 49: Concentrations of ammonia, nitrate, phosphorus, and organic carbon in Well MW4, located beneath the feedlot at the site with a geosynthetic liner.

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 about 60 feet per year, assuming a hydraulic gradient of 0.0194 ft/ft (measured head difference between

Wells MW4 and MW7), a conductivity of 3 ft/d for a fine sand (Anderson and Woessner, 1992), and a porosity of 0.35 ft^3/ft^3. The down-gradient wells are between 200 and 300 feet down-gradient of the feedlot. Assuming water moves directly from Well MW4 to the nearest down-gradient wells at a rate of about 60 feet per year, water quality changes are not likely in these wells for another one to three years.

Water quality beneath the former open lot has improved since installation of the manure storage system. Water quality changes are likely due to removal of manure from the site during construction of the manure basin and subsequent limited animal activity on bare soil. Total nitrogen concentrations will likely decrease for several years, although the rate of decrease and final concentrations are unknown. Because of the oxidizing conditions in ground water, nitrate concentrations may continue to increase.

8. 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 36 summarizes excess chemical concentrations at each site. Estimated plume length is included in Table 36. 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 36, 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 36 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.

To compare different types of systems, we ranked sites from low to high excess chemical concentration for each of the chemicals indicated in Table 36. We then conducted Analysis of Variance on the ranks. The results, shown in Table 37, indicate that unlined systems have the highest maximum chemical concentrations, while open lots, earthen, and concrete systems have similar impacts.

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 36: Excess chemical concentrations at sites with manure storage systems older than five years.

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

Table 37: Comparison of average ranks between different liner systems. Different letters within a column indicate average ranks that differed significantly at the 0.05 level using ANOVA.

8.1. Nitrogen

Manure has a high biochemical oxygen demand. Oxygen and nitrate are utilized as electron acceptors when bacteria consume organic carbon as a food source. Consequently, nitrate concentrations are low in feedlot waste, while concentrations of ammonia and organic nitrogen are high. We observed high concentrations of ammonia and organic nitrogen in many ground water samples down-gradient of manure storage basins.

There are two potential concerns with nitrogen in ground water beneath feedlots. First, ammonia will be a concern when ground water containing feedlot contaminants discharges to surface water. The Class 2A Aquatic Life Standard for ammonia is 0.040 mg/L. Background concentrations of ammonia in ground water are about 0.050 mg/L (MPCA, 1998a). Consequently, any ammonia added to ground water that discharges to a surface water body potentially increases the exposure risk for aquatic organisms to concentrations exceeding surface water criteria.

The second concern with nitrogen in ground water is that ammonia can be converted to nitrate down-gradient of the storage system. This occurs when oxygenated water mixes with ground water containing ammonia. At sites E2 and E3, and C1, we observed higher nitrate concentrations in wells down-gradient of the storage systems compared to up-gradient wells. Only at Site E2, however, did the quantity of nitrate added to ground water from the manure system exceed the drinking water standard of 10 mg/L. At each of these sites, ammonia was probably leaching through the liner into the vadose zone, where it was being converted to nitrate. At sites E2 and E3, depth to ground water was more than 30 feet. These results suggest that deep water tables and permeable soils represent a condition where earthen-lined systems can contribute directly to nitrate contamination of ground water.

Table 38 summarizes a comparison of median up-gradient and down-gradient concentrations of ammonia at each site. At sites with open feedlots, concentrations of ammonia were similar in up-gradient and down-gradient wells. Ammonia may be adsorbed or volatilize from poorly-drained soils at open lots. Concentrations of ammonia under unlined and some earthen-lined systems are high and represent a potential risk to surface water if the ground water discharged to a surface water body.

At most of the sampled sites, nitrate-reducing conditions occurred down-gradient of the manure storage basin or open feedlot. If this ground water becomes oxidized (for example, as a result of mixing with oxygenated recharge water), reduced nitrogen is converted to nitrate. To estimate the potential risk of nitrate contamination, we compared total nitrogen concentrations in down-gradient wells with concentrations in up-gradient wells. The difference represents the amount of nitrogen, or excess nitrogen, added to ground water from the manure storage system. Table 39 indicates excess nitrogen concentrations added to ground water were greatest with unlined systems. At a distance of 50 feet down-gradient of the manure storage system, the median excess nitrogen concentration was 284.7 mg/L with unlined systems, compared to 66.1

Site	**Up-gradient (mg/L)**	**Down-gradient (mg/L)**
O1	0.12	0.10
O2	0.43	0.10
O3	0.09	0.27
O4	0.02	0.10
U1	0.05	26.4
U2	0.08	136
U3	0.020	0.10
E1: basin 1	0.05	8.78
E1: basin 2	0.16	1.23
E2	0.020	4.10
E3	0.25	0.50
C1: basin 1	0.03	0.07
C1 basin 2	0.03	0.08
C2	0.63	2.29

Table 38: Comparison of ammonia concentrations up-gradient and down-gradient of the manure storage systems at each of the sites storage systems older than five years. O = open lot sites, U = sites without a constructed liner (unlined), E = sites with earthen liners, and C = sites with concrete liners.

for open lots, 41.4 mg/L with earthen basins, and 40.9 mg/L with concrete-lined systems. Each of these represents a potential drinking water concern if all nitrogen occurred as nitrate, since the nitrate drinking water standard is 10 mg/L. At a distance of 100 to 200 feet down-gradient of the manure storage system, excess nitrogen was 33.6 mg/L for unlined systems, 28.9 mg/L for open feedlots, 9.1 mg/L for earthen-lined systems, and 6.2 mg/L for concrete-lined systems. These calculations represent a worst-case scenario for unlined, concrete, and open lot systems, because nitrate-reducing conditions occurred down-gradient of the storage systems and it is unlikely that there would be sufficient conversion of ammonia to nitrate to represent a drinking water concern. For earthen-lined systems, however, oxidizing conditions occurred at two sites. Excess nitrogen at these two sites was about 41 mg/L and nitrogen occurred in the nitrate form. Nitrate is mobile and slowly attenuated in ground water, and long nitrate plumes can develop under the conditions observed at these two sites.

	Excess nitrogen	
Site	**50 feet**	**100 to 200 feet**
	mg/L	
O1	7.30	4.9
O2	68.5	- [1]
O3	33.0	29.6
O4	12.2	11.9
U1	615	473
U2	221	10.9
U3	284	-35
E1: basin 1	143	25.7
E1: basin 2	6.44	4.2
E2	48.2	22.2
E3	18.4	1.0
C1: basin 1	13.2	-2.9
C1: basin 2	2.70	7.6
C2	64.4	- [1]

[1] There is no well 100 to 200 feet down-gradient of the manure storage area

Table 39: Excess nitrogen in wells 50 feet and 100 to 200 feet down-gradient of manure storage areas.

All sites we sampled were in row-crop agricultural settings. Nitrate concentrations were typically greater than 20 mg/L and often more than 40 mg/L up-gradient of the manure storage systems. Although excess nitrogen generated through leachate from manure storage systems exceed background nitrate concentrations, the risk to drinking water receptors from manure storage systems was lower than that associated with row-crop agriculture. This is because excess nitrogen at most sites was associated with reduced nitrogen. This nitrogen is attenuated much more quickly than nitrate in ground water. Also, plumes originating from a manure storage system are relatively narrow and impact a small portion of an underlying aquifer compared to row crop agriculture, which may impact a significantly larger area. Management of these types of sources may differ, however, since feedlots represent a point source of nitrogen and row-crop agriculture represents a nonpoint source.

8.2. Phosphorus

Phosphorus represents a concern when discharged to surface water. Ground water represents a potential source of discharge to surface water. Phosphorus loading of surface water leads to algae blooms and oxygen depletion. Average phosphorus concentrations in central Minnesota lakes are 0.050 mg/L or less (MPCA, 2001). Most of the older feedlots examined during this study were located in central Minnesota. Background concentrations of phosphorus in ground water were less than 0.050 mg/L at most sites.

Figure 50 illustrates phosphorus concentrations in ground water for different storage systems. To calculate this value, we used the highest concentration in down-gradient wells at each site. This was usually the well closest to the manure storage area. We then calculated the median of these values for each type of manure storage system. The resulting value represents a worst-case scenario for phosphorus contamination in ground water. Open lots had the lowest concentrations. Possible reasons for this include greater soil thickness, and hence adsorption capacity, compared to other systems, and high concentrations of non-extractable phosphorus. Concentrations of phosphorus in ground water were highest at unlined sites.

Most of the phosphorus leaching into the vadose zone occurs in the organic form. About 25 percent of total phosphorus down-gradient of earthen- and concrete-lined sites occurred as phosphate, while only four percent occurred as phosphate beneath unlined systems. The concentration of phosphate in ground water was similar between the different manure systems. Organic phosphorus is strongly adsorbed and sparingly soluble (Robertson et al., 1998).

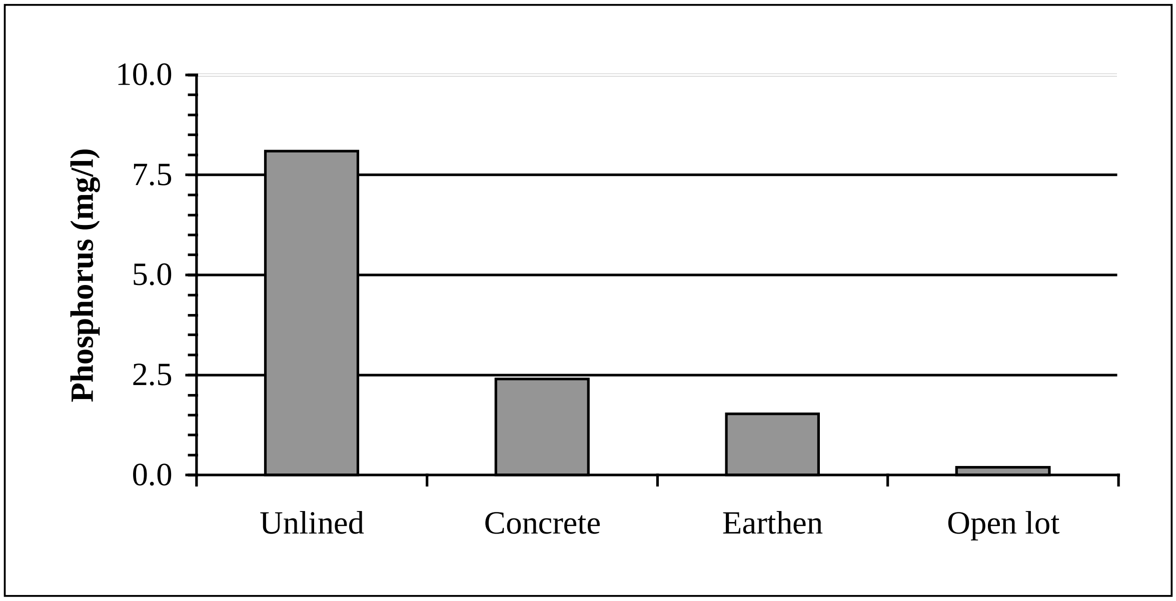

Figure 50: Median phosphorus concentrations for different manure storage systems.

Phosphorus in inorganic forms precipitates with iron and aluminum oxides (Harman et al., 1996). The capacity of soil to carry out precipitation reactions is limited, however. Large quantities of manure effluent rapidly consume this attenuation capacity, particularly when a storage system is in close proximity to the water table. Once in ground water, adsorption controls the fate of phosphorus. Consequently, phosphorus is not very mobile in ground water.

Phosphorus was strongly attenuated in feedlot plumes. Concentrations at most sites approached background concentrations within 100 feet of the storage system. Concentrations of more than 1.0 mg/L were not observed more than 50 feet from a storage system. Thus, although phosphorus concentrations were high immediately down-gradient of some manure storage systems, potential impacts to surface water can be minimized by creating appropriate separation distances between the storage system and a surface water body.

8.3. Organic Carbon

Typical concentrations of organic carbon in ground water are less than 4.0 mg/L (MPCA, 1998a,b). Elevated concentrations of organic carbon in ground water down-gradient of a manure storage basin may be an indication of manure leaching. Organic carbon may contain pathogens and affects the fate of other chemicals in ground water.

Figure 51 shows median concentrations of excess organic carbon in down-gradient wells. Concentrations were highest at sites with unlined systems (38.2 mg/L) and lowest at sites with open lots (1.4 mg/L). The low concentrations at open lots partly reflect attenuation of organic carbon in soil.

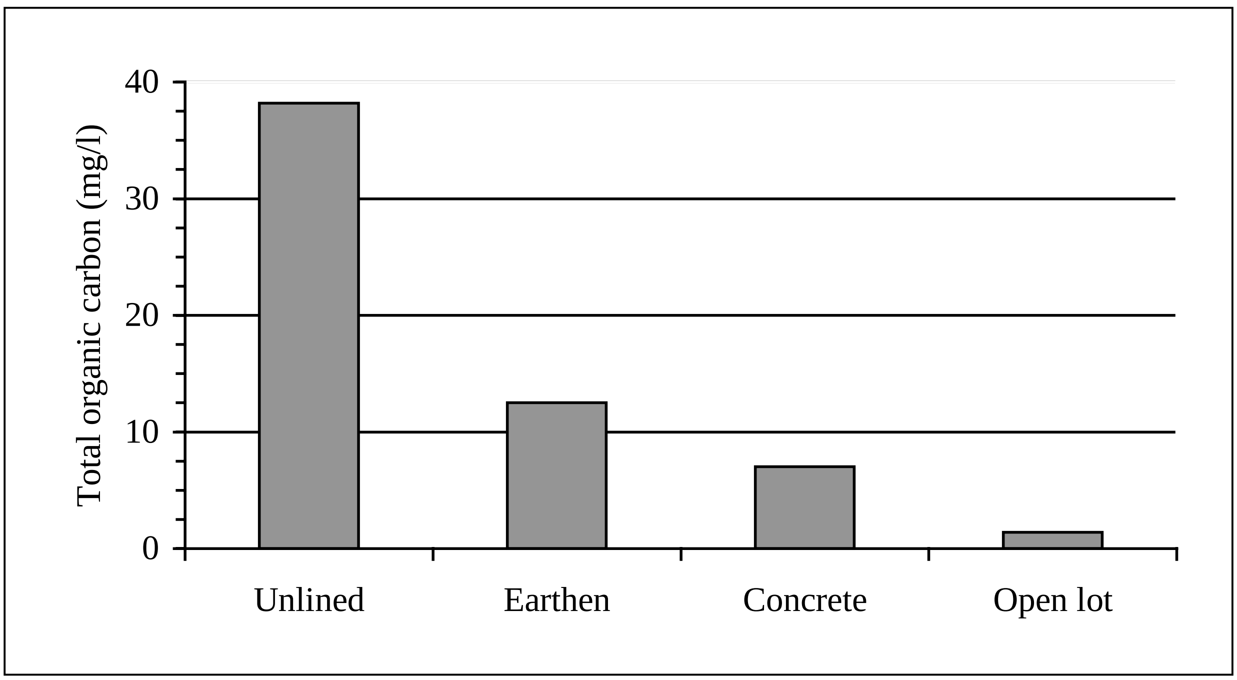

Figure 51: Average concentrations of total organic carbon under four different manure management systems.

Table 40 summarizes correlation coefficients between organic carbon and other chemicals and illustrates the potential importance of organic carbon in ground water. Each of the relationships shown in Table 40 was significant at the 0.05 level. Phosphorus and ammonia, two chemicals that can potentially affect surface water quality and aquatic organisms, were strongly

Chemical	Correlation coefficient
Total Kjeldahl nitrogen	0.942
Ammonia	0.921
Phosphate	0.921
Manganese	0.872
Phosphorus	0.861
Copper	0.859
Iron	0.829
Zinc	0.829
Potassium	0.827
Sodium	0.822
Boron	0.781
Chloride	0.770
Magnesium	0.732
Sulfate-S	0.732
Calcium	0.676
Nitrate	0.451
Dissolved oxygen	-0.335

Table 40: Correlation coefficients for organic carbon and several chemicals. All correlations were significant at the 0.05 level, using the Spearman Rank method.

correlated with organic carbon. Oxidation-reduction sensitive chemicals, such as iron, manganese, nitrate, and oxygen, were also strongly correlated with organic carbon concentrations. Organic carbon thus has the potential to affect the fate of chemicals that leach to ground water.

8.4. Bacteria

Bacteria concentrations are high in manure effluent (see Table 1). Bacterial transport beneath feedlots is not well documented, but the behavior of bacteria is probably similar to that in ground water beneath and down-gradient of individual sewage treatment systems (ISTS). There may be differences in bacterial transport within the vadose zone beneath an ISTS and manure storage systems, however. In a functioning septic drainfield, an organic mat forms and is designed to filter out organic matter. Water passing through this zone percolates to the water table under unsaturated conditions and thus contains oxygen and low quantities of organic matter. Under manure storage systems, there may be little filtering in the soil and saturated flow may occur. Bacteria and viruses that do reach ground water may remain viable for several months and travel several hundred feet in an aquifer, although they typically do not travel more than 100 feet from the source of contamination (Reneau, 1978; Yates and Yates, 1988). Bacteria and viruses are typically filtered in soil, but in most manure storage systems, the ability of soil to filter microorganisms is rapidly diminished because of the chemical strength and quantity of manure leachate.

Our data are hampered by a lack of bacteria samples collected up-gradient of manure storage systems. At three sites where we collected both up-gradient and down-gradient samples, results were mixed. At Site U3, *E. coli* bacteria were detected in both up-gradient and down-gradient samples. Concentrations were higher in down-gradient samples. At Site U1, bacteria were detected in down-gradient samples only, while at Site O4, bacteria were detected only in up-gradient samples. At the site with a geosynthetic liner, we collected bacteria samples over the last six sampling events. Bacteria have been detected in both up-gradient and down-gradient wells. Bacteria may be associated with land application of manure. Better sampling design is needed to determine if manure basins contribute to bacterial and viral contamination of ground water.

8.5. Other Inorganic Chemicals

In addition to nitrogen, organic carbon, and phosphorus, most feedlot plumes are characterized by high concentrations of chloride, potassium, and occasionally other inorganic chemicals such as boron. When nitrate-reducing conditions are encountered beneath and down-gradient of a manure storage system, high concentrations of iron and manganese occur. Table 41 summarizes concentrations of 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 41.

Although concentrations of boron are consistently higher in down-gradient wells, concentrations are below the drinking water standard of 0.60 mg/L. Similar results were observed for chloride and sulfate, although the drinking water standard of 250 mg/L for chloride was exceeded at Site O3. Boron and chloride are mobile in ground water and are good indicators of a feedlot plume. Concentrations of boron and chloride were highest under open lots and unlined systems. Sulfate is also mobile in soil and ground water, but is affected by oxidation-reduction reactions.

Site	Location	Boron	Chloride	Iron	Potassium	Magnesium	Manganese	Sodium	Sulfate
O1	Down-gradient	0.085	91.9	9.73	95.1	38.9	1.223	37.0	4.2
O1	Up-gradient	0.025	12.0	0.042	3.62	28.4	0.131	5.2	2.8
O2	Down-gradient	-	4.60	-	-	-	-	23.5	-
O2	Up-gradient	-	4.60	-	-	-	-	13.0	-
O3	Down-gradient	-	398	0.130	251	80.8	6.270	128	-
O3	Up-gradient	-	0.90	0.305	4.05	10.8	0.400	6.9	-
U1	Down-gradient	0.190	169	13.0	183	64.7	0.250	99.8	18.1
U1	Up-gradient	0.057	17.0	0.006	2.37	38.6	0.003	16.3	10.5
E1	Down-gradient	0.003	93.7	0.022	53.8	63.3	1.820	61.4	28.6
E1	Up-gradient	0.002	8.10	0.018	2.2	23.2	0.027	3.5	8.3
E2	Down-gradient	0.004	53.4	0.005	68.9	9.6	1.020	17.0	72.3
E2	Up-gradient	0.003	22.8	0.002	2.5	35.8	0.177	10.2	7.7
E3	Down-gradient	0.032	22.5	0.005	6.07	23.3	1.255	7.6	4.7
E3	Up-gradient	0.024	13.3	0.006	1.66	18.4	0.150	5.5	2.8
C2	Down-gradient	0.076	19.1	0.006	56	37.7	0.177	21.1	12.1
C2	Up-gradient	0.042	28.7	0.003	4.5	35.0	0.028	10.6	6.3

Table 41: Up-gradient and down-gradient concentrations of inorganic chemicals at several sites.

Sodium, magnesium, and potassium are cations that occur in high concentrations in manure. They are adsorbed in soil, but are more mobile than most trace metals. Potassium is strongly adsorbed to clay, but the sites sampled for this study occur on sandy soils. There are no drinking water criteria for these chemicals. Potassium and sodium appear to be good indicators of a feedlot plume, although there will be retardation of these chemicals in ground water because of adsorption. Concentrations of sodium and potassium were highest under open feedlots and unlined basins.

Potassium displaces calcium and magnesium on clay exchange sites. Calcium to potassium (Ca:K) ratios in ground water are generally greater than 20, but Ca:K ratios in manure range from 1 to 5. As potassium-enriched water infiltrates an aquifer, potassium displaces calcium. The Ca:K ratio thus increases at the front of the manure leachate. Once soils become saturated with potassium, the Ca:K ratio drops rapidly and reflects the Ca:K ratio of liquid manure. Ca:K ratios are therefore indicators of the liquid manure front. We did not have sufficient sampling density to locate the front of liquid manure plumes, but we observed variability in Ca:K ratios adjacent to and down-gradient of manure storage systems. Table 42 shows that Ca:K ratios in up-gradient samples (30.1) are typical of ambient ground water in Minnesota (MPCA, 1998b), while ratios adjacent to manure storage systems are much lower (4.8). Table 42 also indicates that manure plumes often extend for several hundred feet, since Ca:K ratios are suppressed in down-gradient wells. Data in Table 42 are biased, however, since the ratios reflect data from all the feedlots sampled during the temporary well investigation. Since we did not drill wells more than 200 feet from concrete-lined systems, the ratio for far down-gradient well locations reflects only sites with unlined basins, open feedlots, and earthen-lined basins.

Location[1]	**Ca:K ratio**
Adjacent to manure storage	4.8
Close down-gradient	15.9
Far down-gradient	14.6
Up-gradient	30.1

[1] Adjacent to manure storage includes wells completed beneath open lots or within 25 feet of a manure storage basin; close down-gradient wells are within 50 to 200 feet of the basin or open lot; far down-gradient are more than 200 feet from the basin or open lot.

Table 42: Calcium to potassium ratios (Ca:K) for different well locations. Ratios were calculated considering data from all feedlot sites.

Iron concentrations were more than 9 mg/L at Sites O1 and U1 and exceeded the Secondary Maximum Contaminant Level of 0.300 mg/L. Since we filtered samples using a 0.45-um filter, this iron is predominantly in the ferrous (+2) form. The high iron concentrations were therefore related to reducing conditions beneath the feedlots. At Site O1, iron concentrations decreased rapidly down-gradient of the open lot. At Site U1, iron concentrations exceeded 10 mg/L more than 300 feet from the manure basin. Site U1 represents a highly impacted site where reducing conditions are maintained down-gradient of the storage system. Manganese, like iron, is affected by oxidation-reduction conditions. Manganese concentrations exceeded the drinking water criteria of 1.0 mg/L[10] in down-gradient wells at five sites. High concentrations of

[10] The current drinking water standard (HRL) for manganese is 0.10 mg/L. We use a value of 1.0 mg/L for the drinking criteria based on a recommendation by the Minnesota Department of Health (MDH, 1997)

manganese persisted in down-gradient wells at Sites O1, O3, and E1. Manganese concentrations increased down-gradient at Site U1, which is a highly impacted site. Most of this manganese is likely to be in reduced form, indicating that a nitrate-reducing plume persisted for several hundred feet down-gradient of most manure storage systems. This was true even for the concrete-lined systems, although manganese concentrations were much less than under the other types of systems. The length of these reducing plumes provides a benefit for nitrogen, since ammonia is attenuated in a plume. By the time oxidizing conditions occur down-gradient of the storage system, most ammonia from the storage system has attenuated.

9. Comparative Risk and Multimedia Analysis

In addition to potential impacts to ground water, manure management systems have the potential to impact surface water through overland runoff of manure contaminants, and air through release of manure gases. Manure may affect each of these media when it is applied as a fertilizer to agricultural soils. We did not conduct multimedia analysis in this report, nor did we conduct comparative risk assessments. Comprehensive environmental management requires consideration of both multimedia and comparative risk analyses.

Comparative risk refers to the potential risk associated with one management activity relative to others. For example, in Section 8.1 we discuss excess nitrogen added to ground water from manure storage systems. Although excess nitrogen added from manure storage systems may be as much as 200 mg/L from unlined basins, this nitrogen is generally in a reduced form and does not represent a drinking water concern. Relative to row crop agriculture, manure management systems have a very small area of impact. Locally, however, a manure management system can dramatically impact receptors if a well or surface water intersects a liquid manure plume. Consequently, an important tool for risk reduction in manure management is proper placement of a manure storage system relative to potential receptors. Within wellhead protection areas, it may be important to identify not only the location of feedlots, but the type of manure storage used at each feedlot and ground water flow direction. It may be particularly important to identify open feedlots and unpermitted manure basins in wellhead protection areas, since these may eventually be abandoned. Abandoned feedlots often represent a concern for drinking water receptors, since soils at these feedlots contain large quantities of nitrogen. Soils often become more permeable after abandonment, leading to conditions where ammonia can be converted to nitrate.

Multimedia analysis considers the cumulative impacts from different pollution sources. Pollution sources include those that impact water, soil, and air, as well as different pollutants. In an agricultural setting, for example, nitrogen pollution sources include row crop agriculture (impact water and soil), manure storage systems (impact water and air), storage tanks (impact water and soil), and ISTS (impact water). Pollutants could also include other nutrients, pesticides, and petroleum products.

10. 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.
7. 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