APPENDIX E

Minnesota Pollution Control Agency Paper

Effects of Septic Systems on Ground Water Quality - Baxter, Minnesota

May, 1999

Published by

Prepared by

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Executive Summary

In 1998, the Minnesota Pollution Control Agency (MPCA) conducted a study to determine the effects of septic systems on ground water quality in residential areas of Baxter, Minnesota. The Baxter area is experiencing rapid expansion with unsewered developments. A sensitive aquifer underlies the study area. Numerous lakes are in direct connection with ground water and may be impacted by septic discharges to ground water.

The study was conducted in two phases. In Phase 1, 40 permanent domestic and 12 temporary wells were sampled at different depths in the shallow sand aquifer. Nitrate was the primary chemical of concern. Median nitrate concentrations were significantly higher in areas with Individual Sewage Treatment Systems (unsewered areas; 1980 ug/L or parts per billion) than in areas served by municipal sewers (sewered areas; 778 ug/L). All four exceedances of drinking water criteria (10000 ug/L) were in unsewered areas. Nitrate concentrations were highest in the upper 15 to 20 feet of the aquifer, then decreased rapidly with depth. Denitrification most likely accounts for the decrease in nitrate with depth. Total and dissolved organic carbon were also greater in unsewered areas.

The objective of Phase 2 was to examine concentrations of chemicals within ground water plumes originating beneath individual septic systems. Plumes were observed beneath each of the seven systems sampled. The average plume length was approximately 25 meters and ranged from 10 to over 100 meters. Chloride was used as an indicator of the septic plume. At each site, nitrate concentrations exceeded the drinking water criteria throughout most of the plume. Nitrate concentrations decreased slowly along the plume lengths, as indicated by decreasing nitrate to chloride ratios. If the plumes studied are typical of plumes throughout Baxter, one acre lots should result in about 7 percent of the shallow portion of the aquifer having nitrate concentrations above the drinking standard. Twenty-five percent of the geoprobe wells drilled during Phase 1 exceeded the HRL, however. The higher than expected rate may be due to biases in sampling, inputs from fertilizers, lot sizes smaller than one acre, or typical plumes being longer than those that were sampled.

Bacteria and Volatile Organic Compounds (VOCs) were found in septic effluent at all seven sites. Most probable number concentrations of total coliform were as high as 200000/100-mL. These concentrations are similar to those observed in the literature. Concentrations of coliform bacteria in ground water decreased by two orders of magnitude within 15 meters of the drainfield. Total VOC concentrations in septic tanks ranged from 138 to 800 ug/L. The most common VOCs were substituted benzenes, which accounted for about 67 percent of the 41 total detections. There were thirteen VOC detections in ground water, eleven of which were chloroform. There were no exceedances of drinking water criteria for VOCs.

Phosphorus is an important chemical of concern in northern Minnesota because of the recreational value of lakes. There were no significant differences in phosphorus concentrations in ground water under sewered and unsewered areas. Phosphorus concentrations in septic plumes approached background concentrations within 12 meters of the drainfield. Phosphorus from septic systems does not represent a threat to surface water based on results of this study. Further investigations may be required for more sensitive environments, such as in areas with a large number of nonconforming systems, in aquifers that have low pH and are poorly buffered, and in areas where drainfields are close to lakes that lack riparian buffers.

The results for Baxter differ from St. Cloud, where concentrations in unsewered areas approach the drinking water standard for nitrate. Residential areas in St. Cloud are older than those found in Baxter. Lot sizes are also smaller in St. Cloud. Additional Phase 1 sampling is recommended in other unsewered areas of Minnesota. Sampling should focus on residential areas with differing lot sizes and ages of development, since individual plumes may take several years to stabilize. This information can be used to assess potential risk to drinking water receptors for new communities or communities considering sewering.

The plume investigations in this study were not sufficiently rigorous to evaluate three important aspects of sewage effects on ground water. First, none of the seven sampled plumes appeared to discharge to a lake. Additional efforts to track septic plumes into lakes should focus on probing parallel to shorelines so that plumes can be identified

close to the ground water-surface water interface. Second, a one-time sampling for bacteria does not address temporal variations in populations, although literature indicates this is a very important factor. Virus behavior in septic systems was also not studied, and viruses potentially have more serious health impacts than bacteria. Third, effects of hydrology on water quality within plumes could not be addressed. Measurements of recharge, response to precipitation, and measurement of physical parameters (using slug tests) are necessary to determine how a plume behaves in response to hydrologic factors.

An important consideration in ground water monitoring of septic systems is the change in water quality following sewering. This monitoring work is not recommended for Baxter at this time. The median nitrate concentration of 1980 ug/L (parts per billion) under unsewered areas, although higher than the concentration under sewered areas, is well below the drinking water standard. The area will largely be sewered within the next five years, which should prevent further degradation of ground water with nitrate. The low concentrations prevent easy evaluation of water quality changes following sewering.

Introduction

Septic systems are designed to treat human waste. Properly functioning systems attenuate organic matter, microbes, and most cations, but not anions. Systems that have are placed close to the zone of saturation are effective in attenuating nitrogen, but are ineffective at attenuating pathogens, organic matter, and phosphorus (Noss and Billa, 1988; Kaplan, 1987).

There are nearly half a million septic systems servicing over a million people in Minnesota. Septic system effluent discharged to the unsaturated zone reaches ground water, where it impacts water quality. Chemical concentrations in drainfield effluent vary with the type of use. For a typical household using the drainfield for discharge of drinking, shower, toilet, and laundry water, concentrations of nitrogen, sodium, potassium, bicarbonate, chloride, phosphorus, and carbon are greater in septic effluent than in ground water.

Septic waste discharged to coarse-textured soils proceeds vertically through the unsaturated zone and into ground water. Once in ground water, a septic plume develops and moves with ground water flow. Approximate times for septic effluent to pass through the unsaturated zone to ground water range from a few hours to fifty days, depending on the volume of effluent and the distance to ground water (Robertson et al., 1991; Robertson, 1994; Robertson and Cherry, 1995). A septic plume in ground water moves at a rate similar to the ground water velocity.

Chloride is potentially a good indicator of a septic plume, while sodium, pH, and specific conductance may occasionally be useful for delineating a plume. Vertical and lateral (transverse) dispersion of the plume are small, being about 1 and 10 percent, respectively, of the horizontal (longitudinal) dispersivity (Childs et al., 1974; Brown, 1980; Anderson et al., 1987; Harman et al., 1996; Robertson et al., 1991).

Pathogens present in septic tank effluent are usually attenuated in the soil treatment system. Attenuation occurs within a clogging mat, which occurs at the interface between native soils and drainfield media. If the seasonal high water table is less than three feet from the system bottom, or if there is preferential flow of sewage for systems without a clogging mat, microbes can reach ground water. Several cases of bacterial and

viral transport for long distances in ground water have been documented (Yates and Yates, 1988; Brown, 1980; Hagedorn et al., 1978; Reneau, 1978; DeBorde et al., 1998). Virus transport can be extremely rapid in ground water. Yates and Yates (1988) observed virus transport of 400 feet within 100 days.

Wilhelm et al. (1994) and Brown (1980) report that most phosphorus goes into the septic tank in organic forms, but that orthophosphate accounts for about 80% of the total phosphorus in the tank effluent. Phosphate precipitates in the unsaturated zone or is adsorbed in the aquifer close to the drainfield. In old systems, the attenuation capacity within the unsaturated zone diminishes and phosphate can reach ground water and move down-gradient in the septic plume. Robertson et al. (1998) observed phosphate migration exceeding 10 meters in six of ten plumes investigated. In contrast, Harman et al. (1996) observed phosphate concentrations of less than 1000 ug/L within ten meters of the drainfield for a 44-year old system servicing an elementary school. Movement of phosphate rarely exceeds 5 meters, even in very old systems (Wilhelm et al., 1994). Phosphate may be a concern in poorly buffered systems if the pH within the plume drops below 6.0.

Volatile Organic Compounds (VOCs) and most semi-volatile organic compounds are not a component of human waste. Oil and optical brighteners, however, are commonly found in laundry effluent (Fay et al., 1995; Alhajjar et al., 1990; Kaplan, 1987). Some VOCs have been used for odor control (Robertson, 1994), while VOCs may also be introduced into septic systems after household use (e.g., paints, varnishes, degreasers). Some organic compounds may be present as breakdown products of human waste (Muszkat et al., 1993). Many organic compounds will be conservative in ground water, particularly halogenated VOCs.

There is little information on the fate of trace inorganics in septic plumes. Concentrations of these chemicals, including heavy metals, are typically low in human waste (Wilhelm et al., 1996; Robertson and Blowes, 1995). Concentrations of trace inorganics may reach levels of concern in poorly buffered ground water systems where the pH within the plume falls below 6.0 (Robertson and Blowes, 1995).

Nitrate is the primary chemical of concern in most septic plumes. Nearly all nitrogen passing through the drainfield converts to nitrate in the aerobic soil zone and eventually leaches to ground water (Brown, 1980; Walker et al., 1973; Wilhelm et al., 1996; Kaplan, 1987; Robertson and Cherry, 1995). Nitrates are conservative in shallow ground water because oxygen is present and total organic carbon concentrations are too low to sustain intensive microbial activity (Wilhelm et al., 1996), although Steinheimer et al. (1998) suggest autotrophic denitrification (non-organic food source) may be an important mechanism of denitrification. Nitrate plumes slowly attenuate as a result of dilution from recharge water and dispersion within the aquifer. Nitrate concentrations can exceed drinking water criteria at distances of 100 meters or more from the drainfield.

Predicting nitrate concentrations in an unsewered area consists of quantifying the contribution of each system. It is difficult, however, to predict the nitrate concentration in specific locations because plumes may mix and the fate of individual plumes is unknown. In addition, seasonal changes in ground water flow may occur because of different inputs from the septic system, effects of surface water bodies, and local pumping from wells.

Researchers have used different approaches to quantify or predict nitrate distribution in unsewered areas. Hantzsche and Finnemore (1992) drilled several wells in three different unsewered developments and reported mean nitrate concentrations of 9600 to 13900 ug/L. Concentrations in individual wells ranged from less than 3000 ug/L to 65000 ug/L. Quan et al. (1974) sampled several domestic wells in a deep sand and gravel aquifer and found concentrations between 5000 and 11000 ug/L. Harmsen et al. (1996) installed multilevel wells along two hydrologic transects in two separate unsewered subdivisions with lot sizes ranging from 0.5 to 0.7 acres. Concentrations of nitrates ranged from 5000 to 15000 ug/L, with average concentrations of 6000 to 8000 ug/L. Tinker (1991) measured nitrate concentrations in residential wells in five unsewered subdivisions with lot sizes ranging from 0.5 to 1.1 acre. Concentrations gradually increased from 1000 to 13000 ug/L from the up-gradient to the down-gradient edge of the subdivisions. Miller observed median nitrate concentrations of 2000 and 13000 ug/L in ground water under half acre lot developments that were two and 15 years old, respectively. Although water quality of individual septic systems are similar regardless of

age, ground water quality within an aquifer will continue to change until plumes from individual systems stabilize.

Several researchers have attempted to predict nitrate distribution using hydrologic models (Hantzsche and Finnemore, 1992; Anderson et al., 1987; Baumann and Schafer, 1984). Lot sizes less than 1.0 acre in size in sandy soils result in nitrate concentrations exceeding the drinking water criteria of 10000 ug/L over a significant portion of the aquifer.

Despite the vast amount of information on ground water quality associated with septic wastes, there are research gaps. Researchers have provided limited information regarding the overall spatial distribution of nitrate in an unsewered subdivision. Because of this, there is little information useful for quantifying the risk that a particular well will exceed the drinking water criteria. Since most research has focused on behavior of individual systems, predictive modeling has used plume information in conjunction with hydrogeologic information to predict nitrate distributions. This approach lacks calibration of modeling results with data from an entire unsewered subdivision. There is little information describing effects of septic systems on surface water (Magner and Regan, 1994). Finally, there have been few long-term monitoring studies conducted in changing land use settings, such as when an unsewered area is sewered.

We initiated a study in 1998 to assess the environmental impact of on-site sewage disposal systems on ground water quality. The objectives of the study were to

1. determine the spatial distribution of nitrate in ground water across an unsewered development; and

2. delineate individual septic plumes and determine the distribution for chemicals of potential concern within the plumes.

Information from this study may be useful in assessing nutrient loading to lakes from septic systems, determining overall patterns of risk to human and ecological receptors resulting from septic system discharges, and developing predictive models.

Methods and Materials

The study was conducted in the City of Baxter, located in east-central Minnesota (Figure 1). The Branierd-Baxter area has a population of approximately 40000 and is undergoing rapid expansion with unsewered developments. Many of these developments consist of lakeshore or near lakeshore property. The study area is located in an area of sandy soils underlain by a sensitive sand aquifer. Many unsewered developments will be sewered within the next ten years. Figure 2 illustrates the location of unsewered areas within the study area.
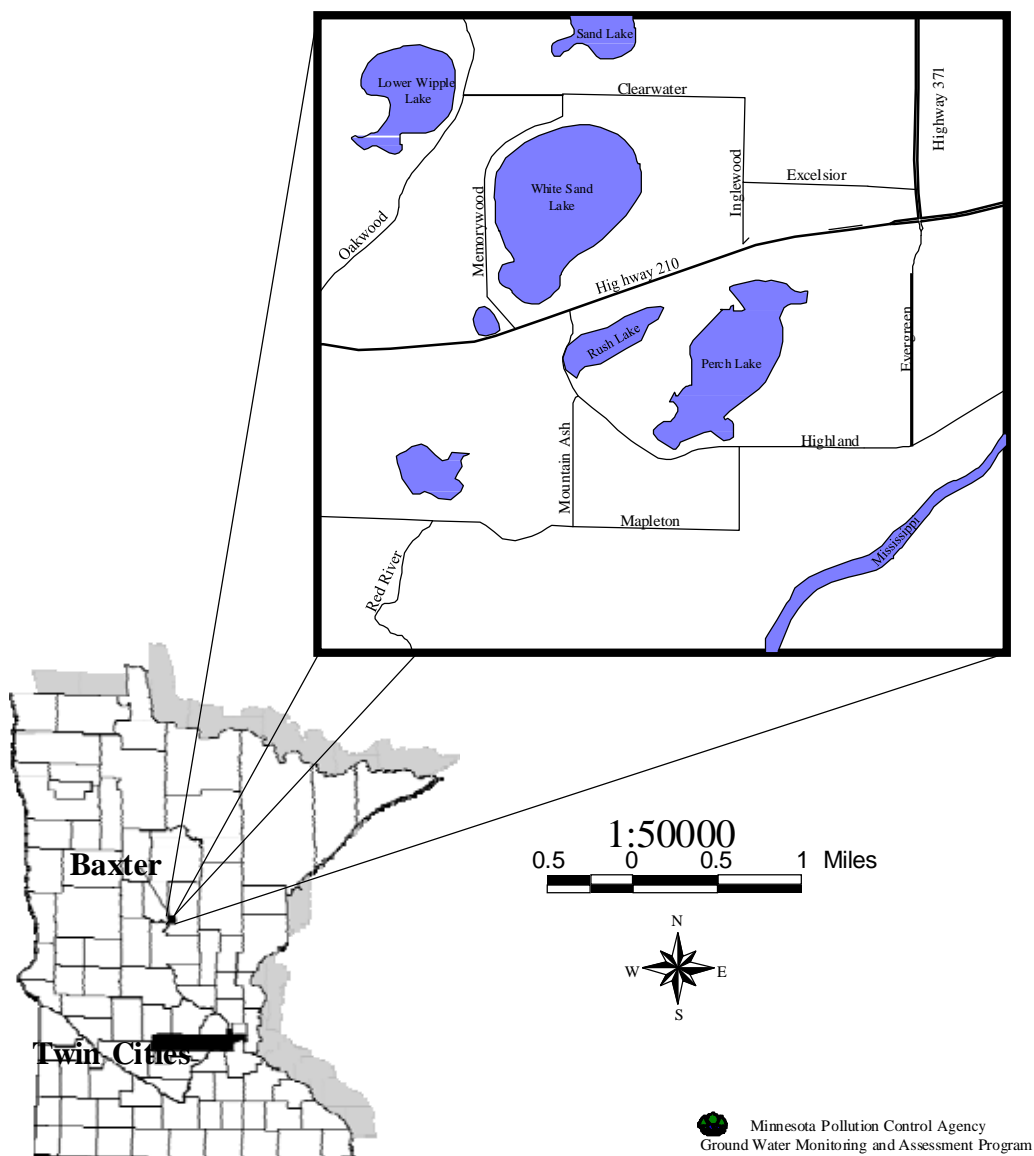
Figure 1 : Location of Baxter study area.
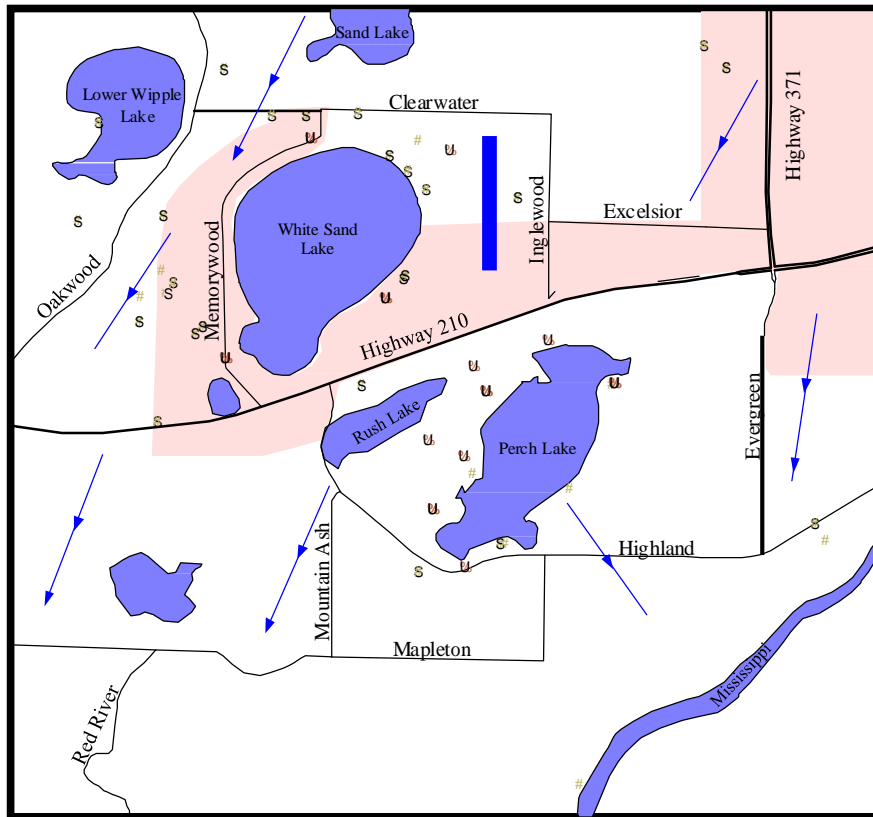
Figure 2 : Map of the study area illustrating sewered and unsewered areas, ground water flow direction, and sampling locations.

The surficial geology consists of outwash deposits of sand and gravelly sand associated with the Wadena Lobe. Localized alluvium consisting of less than six feet of silt loam and loamy sand occurs along the Crow Wing River. Isolated peat deposits and sandy till lenses are found in the study area but comprise small areas. Peat deposits, where they are mapped, are associated with organic deposits greater than three feet in thickness and are found in marshes, often adjacent to lakes and drainageways. Till deposits

associated with the Wadena Lobe are sandy loam, unsorted, and become very dense with depth. Precambrian age deposits underlie the area, but these are more than 100 feet below the land surface and are unimportant hydrologically.

Soils belong to the Menahga and Zimmerman series. Menahga (Typic Udipsamment) consists of light colored, well drained, medium acid loamy soils 4 to 8 inches thick over fine sand. Sands are limy below 4 to 6 feet. Zimmerman (Alfic Udipsamment) consists of light colored, excessively drained loamy fine sands or fine sands over acid fine sand and medium sand. Peat occurs in depressions over approximately five percent of the area. Poorly drained sandy tills, such as those from the Lino series, occur as lenses within the well-drained sands. Native vegetation is predominantly jack pine.

Average annual precipitation in the study area is about 24.8 inches, 11 of which falls between June and August. Average July and January temperatures are approximately 70 and 10 ^{o}F, respectively. The frost-free period extends from mid-May to late-September. A National Weather Service station is located at the Branierd airport.

Ground water flows toward the Mississippi River and through the lakes in the area, as illustrated in Figure 2. During late summer and through winter, ground water generally flows out from the lakes. Annual recharge to the aquifer is approximately six inches a year.

Phase 1

The objective of Phase 1 was to determine the distribution of chemicals, particularly nitrate, across sewered and unsewered areas.

Design and Data Collection

We sampled 40 domestic wells, screened at depths of 0 to 60 feet below the water table. Figure 2 illustrates sampling locations. The County Well Index (Wahl and Tipping, 1991) provided drilling and geologic information for several hundred wells. The sampling locations include a range of well depths and assure an approximately even distribution of wells across the study area.

Field sampling methods are described in MPCA, 1998a. Sample collection for domestic wells consisted of connecting one end of a hose to an outside spigot and the other end to a YSI 600XL[1] multiparameter probe. Once the spigot was turned on, continuous measurements of oxidation-reduction potential (mV), temperature (^{o}C), pH, specific conductance (umhos/cm), and dissolved oxygen (mg/L) were taken. Samples were collected once temperature, specific conductance, and pH had stabilized to 0.1^{o}C, 10%, and 0.1 pH unit, respectively, for three successive readings. At 28 sites, nitrate was analyzed in the field using a Hach DR/4000 Spectrophotometer. The remaining 12 samples were analyzed at the University of Minnesota Research Analytical Laboratory using the cadmium reduction method and a reporting limit of 10 ug/L. Alkalinity, chloride, and sulfate were measured in the field using commercially available field test kits.

We selected twelve additional locations for geoprobe sampling (Figure 2). Split spoon samples were collected at four foot intervals and textural analysis was performed on the split spoon samples (Table 1). The data indicate soils consist primarily of very fine sands to depths of more than 15 feet. Soil remaining in the 0.1 mm sieve consisted of uniform, very fine sands. Five-foot screens (0.010 slot, threaded PVC) were installed across the water table. Samples were pumped using a peristaltic pump until sample turbidity became uniform and field parameters stabilized. At five sites, an additional sample was collected 5 to 10 feet below the water table. Dissolved oxygen, oxidation- reduction potential, pH, temperature, and specific conductance were measured during pumping. Alkalinity, nitrate-nitrogen, chloride, and sulfate were measured in the field using commercially available field test kits. Laboratory analysis included major cations and anions, dissolved and total organic carbon, ammonia-nitrogen, and total Kjeldahl nitrogen. Reporting limits and analytic methods are summarized in Table 2.

Sample ID	Depth (ft)	% by Weight				
		> 1 mm (V. Coarse)	1 - 0.5 mm (Coarse)	0.5 - 0.25 mm (Medium)	0.25 - 0.1mm (Fine)	< 0.1 mm (V. Fine)
1	0-4	0.0	0.7	1.9	27.0	70.4
	4-8	0.0	2.6	8.5	41.3	47.7
Sample	Depth (ft)	% by Weight				
		> 1 mm	1 - 0.5 mm	0.5 - 0.25 mm	0.25 - 0.1mm	< 0.1 mm cation

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[1] Mention of a particular product does not represent endorsement of or preference for that product.

ID		(V. Coarse)	(Coarse)	(Medium)	(Fine)	(V. Fine)
2	0-4	0.0	1.0	8.6	59.6	30.8
	4-8	0.0	0.2	1.6	56.3	41.9
	8-12	0.0	1.0	7.6	59.6	31.8
	12-16	0.0	0.4	4.6	60.8	34.2
	16-20	0.0	0.3	2.6	46.4	50.8
	20-24	0.0	0.8	6.2	55.2	37.8
3	0-4	0.0	0.4	3.7	56.2	39.6
	4-8	0.0	0.2	2.5	70.0	27.3
	8-12	0.0	0.4	2.3	44.6	52.8
	12-16	0.0	0.1	0.3	33.2	66.3
	16-20	0.0	0.3	3.0	48.8	47.9
	20-24	0.0	0.3	1.9	65.2	32.5
4	0-4	0.0	0.7	2.5	60.0	36.8
	4-8	0.0	0.1	0.7	40.4	58.8
	8-12	0.5	1.5	5.3	49.7	43.1
	12-16	0.0	0.4	2.4	30.3	66.9
	16-20	0.0	0.6	2.1	31.3	66.0
5	0-4	0.0	0.4	3.1	47.3	49.1
	4-8	0.0	0.3	4.3	48.2	47.1
	8-12	0.0	0.8	8.8	65.0	25.3
	12-16	0.0	0.4	2.6	42.2	54.7
6	0-4	0.0	1.6	5.1	41.4	52.0
	4-8	0.0	2.8	8.4	56.5	32.2
	8-12	0.0	1.6	4.8	53.7	39.9
	12-16	0.0	1.3	2.8	44.1	51.8
7	0-4	0.0	0.7	26.3	63.3	9.6
	4-8	0.0	0.9	19.1	63.6	16.4
8	0-4	0.0	0.9	4.2	55.0	39.9
	4-8	0.0	0.3	1.6	51.5	46.7
	8-12	0.0	1.8	8.3	62.3	27.5
	12-16	0.3	1.1	15.7	62.0	21.0
9	0-4	0.2	1.8	7.8	53.9	36.4
	4-8	0.1	1.0	7.9	50.1	40.9
	8-12	0.0	1.1	6.6	68.8	23.5
10	0-4	0.5	2.3	3.8	33.4	59.9
	4-8	0.0	0.0	0.7	25.1	74.2
	8-12	0.0	0.6	3.7	31.5	64.3
11	0-4	0.2	0.4	6.0	53.6	39.8
	4-8	0.0	0.1	2.3	59.6	38.0
	8-12	0.0	0.2	0.7	36.1	63.0
12	0-4	0.0	0.1	3.5	60.5	35.8
	4-8	0.0	0.9	12.1	58.4	28.6
	8-12	0.8	1.5	6.6	53.1	38.1
	12-16	0.0	0.7	2.7	25.8	70.8

Table 1 : Results of particle size analysis for geoprobe samples.

Parameter	Method	Reporting Limits (ug/l)

NO$_3$-N	Cadmium reduction	500
Total phosphorus, Ca, Mg, Na, K, Fe, Mn, Zn, B	ICP	14, 5, 20, 60, 100, 3.1, 0.9, 1.7, 6.5
Cl, F, SO4, Br	Ion chromatography	100, 200, 100, 200
Dissolved Oxygen	Field meter	300
Alkalinity	Titration	1000
Oxidation-reduction potential	Field meter	1 mV
Total organic carbon	Dohrman carbon analyzer	100
Ammonia	Colorimetric	20
Kjeldahl-nitrogen	Block digestor method	200

Table 2 : Analytic method and detection limit for sampling parameters.

Data Analysis

Statistical methods (MPCA, 1998b) included the Mann-Whitney test for comparison of nitrate concentrations in sewered and unsewered areas, the Spearmann rank method for correlation analysis, and the Kruskal-Walis test for comparison of chemical concentrations between different depth classes. Depth classes included geoprobe samples screened at the water table, geoprobe samples screened below the water table, domestic wells less than 30 feet deep, and domestic wells greater than 30 feet deep.

Phase 2

The objective of Phase 2 was to determine the distribution of chemicals in individual septic plumes.

Design and Data Collection

Temporary wells, installed with a geoprobe, were used to track plumes from seven conventional septic systems with year-round usage for families of 2 to 5 people. Site locations are illustrated in Figure 3. General site information is illustrated in Table 3. Conforming systems are those with three or more feet of soil above the top of the drainfield and no evidence of soil mottling between the bottom of the drainfield and the top of the water table (Wespetal, personal communication). Mottling is used as an indicator of the seasonal high water table, since mottling is considered to occur rapidly

under anaerobic conditions. It is unclear, however, how long the water table must be close to the bottom of the drainfield to affect the hydraulic performance of the system.

We drilled 20 to 30 temporary wells at each site, but only retained samples considered to be from the septic plume. These were samples in which field-measured chloride concentrations were more than twice the measured background concentration.
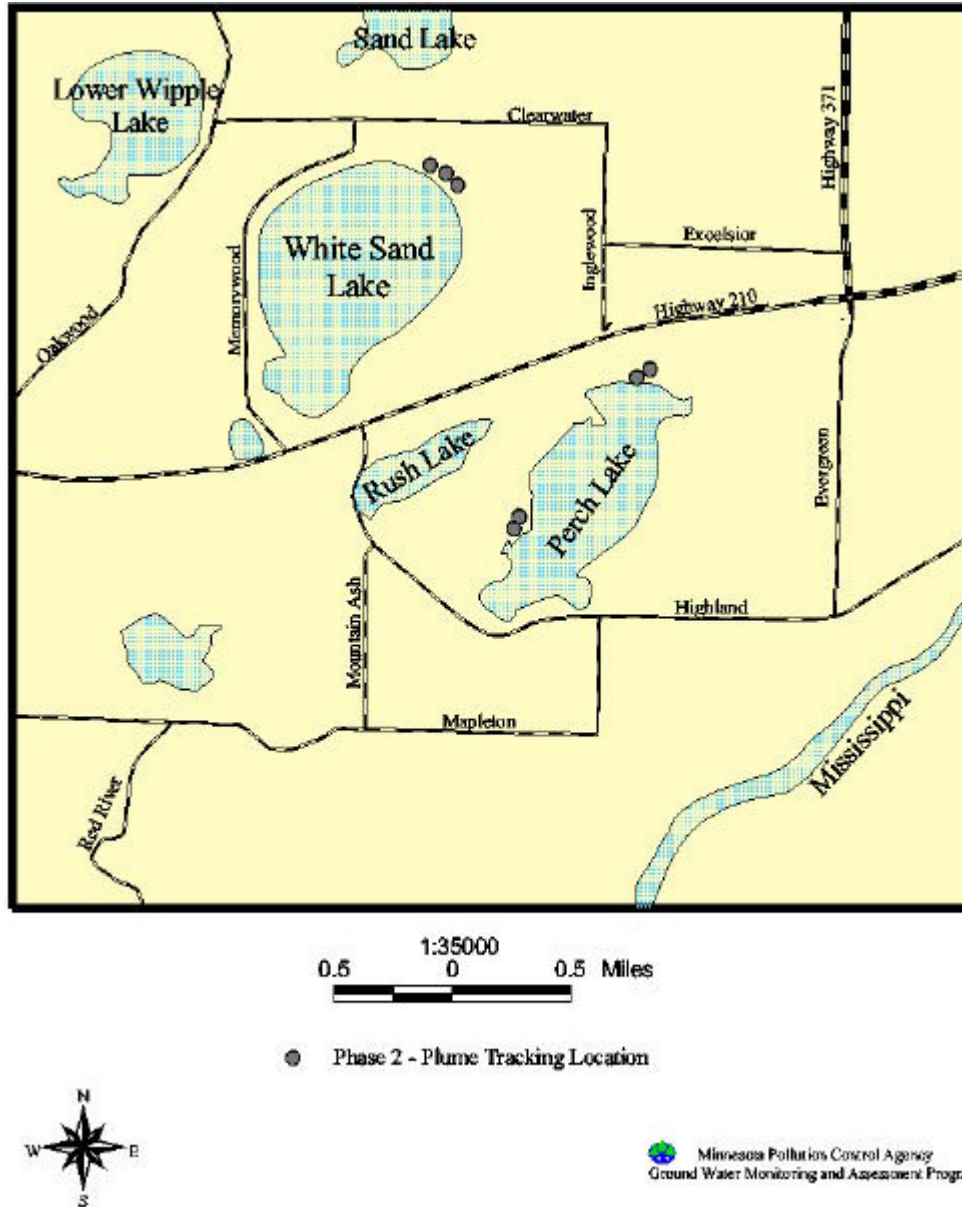

Figure 3 : Location of individual septic systems selected for sampling.

		Conforming	Number of	Last

Site	Description	system	samples collected	pumped
1	Approx. 25 people; > 15 years old[1]	no	16	Sept., 1998
2	2 people; 5 years old	-	9	July, 1995
3	5 people; 15 years old	-	14	-
5	2 people; > 20 years old	no[2]	11	-
6	2 people; 15-20 years old	yes	16	Oct., 1997
7	5 people; 13 years old	no[2]	17	July, 1997
8	2 people; > 20 years old	-	12	July, 1998

[1] System ages are approximate
[2] Less than three feet of unsaturated soil below the soil treatment system to the seasonally saturated layer

Table 3 : Summary information for the plume sites.

Initially, we located the septic tank and installed three temporary wells at each site. We used a regional ground water flow map for Baxter (see Figure 2) and site observations of topography and location of lakes to site wells. One well was installed at the assumed down-gradient edge of the septic system, a second farther down-gradient of the septic system, and a third up-gradient of the system. Well casing tops were surveyed to 0.1 foot and referenced to a fixed benchmark at the site. Depth to water was measured and static water elevations calculated. We conducted similar measurements for each successive temporary well. All well locations were determined with a Global Positioning System.

At each of the first three wells, a five foot screen was installed across the water table. A peristaltic pump was used to purge the well of water. Tubing from the pump was attached to a YSI 600XL multiparameter probe. The wells were pumped until the water was not turbid and pH, specific conductance, and temperature stabilized to 0.1 pH unit, 10%, and 0.1 $^{\circ}$C, respectively, for three consecutive readings. After the well stabilized, samples for laboratory analysis were collected for nitrogen species, major cations and anions, total and dissolved organic carbon, coliform bacteria, and volatile organic compounds (VOCs). Alkalinity, sulfate, and chloride were measured in the field using commercially available test kits.

We drilled additional wells to define the horizontal and vertical extent of the plume. Wells were completed in a manner similar to the first three wells. Field-measured specific conductance and chloride concentrations were used to identify ground water impacted by the septic system. Samples for laboratory analysis included major cations and

anions, total and dissolved organic carbon, nitrogen species, VOCs, total coliform bacteria, and *Escherichia coli (E. Coli)* bacteria.

A sample from the septic tank was taken at each site using a hand bailer. Laboratory analysis of septic tank samples included major cations and anions, coliform bacteria, *E. Coli* bacteria, VOCs, nitrogen species, and total and dissolved organic carbon. Cation and dissolved organic carbon samples were filtered with a 0.45 micron in-line filter (well samples) or a bottle top vacuum filter (tank samples).

We collected two aquifer sediment samples at each site. One of these was in the septic drainfield and another down-gradient of the drainfield. Cation exchange capacity, organic carbon content, and carbonate content were determined for each sediment sample. Following sampling at each site, the drainfield was examined to determine if it met the appropriate criteria for vertical separation between the bottom of the drainfield and the top of the seasonal high water table and between the land surface and and the top of the drainfield (see Table 3).

Data Analysis

Statistical methods included the Mann-Whitney test for comparisons of septic tank effluent and background ground water concentrations, and for comparisons of septic tank effluent and maximum concentrations observed in ground water at each site. Chemicals in which concentrations differed between background and the septic tank were considered to represent chemicals of potential concern associated with discharge from septic systems. We estimated the horizontal migration distance for each chemical and plume by plotting data in Surfer and determining the point where concentrations reached background. Correlation analysis included the Spearmann rank method.

Results and Discussion

Results are discussed separately for Phase 1 and Phase 2.

Phase 1

Table 4 summarizes concentrations of chemicals in geoprobe samples. pH and concentrations of nitrate, dissolved organic carbon, and total organic carbon were greater in unsewered areas than in sewered areas. All three exceedances of the Health Risk Limit (HRL) of 10000 ug/L for nitrate were in unsewered areas. This represents 25 percent of the geoprobe samples collected from unsewered areas. There was one exceedance of the HRL from a domestic well. The elevated concentrations of dissolved and total organic carbon provide evidence of septic impacts since carbon is associated with septic discharge.

Chloride and sodium, often considered to be tracers of septic plumes, did not differ in concentration between sewered and unsewered areas. Human wastes are enriched in sodium and chloride, but road salts are also an important input in sewered areas. Phosphorus concentrations did not differ between sewered and unsewered areas. This is not surprising since phosphorus from septic systems is attenuated near the drainfield. Specific conductance also did not differ between sewered and unsewered areas, even though specific conductance was a good indicator of septic plumes (see Results for Phase 2). Finally, concentrations of ammonia and Kjeldahl nitrogen did not differ between sewered and unsewered areas. Like phosphorus, reduced forms of nitrogen are attenuated close to the drainfield.

Age of development appears to be an important factor affecting the distribution of nitrate in ground water (Figure 4). The highest concentrations of nitrate in shallow ground water were observed northwest of Perch Lake. This is an area that was developed prior to 1990. Development west of this occurred in the 1990's, and nitrate concentrations are lower despite similar lot sizes. Developments dated in the 1960's and 1970's are scattered throughout the study area. We collected an insufficient number of samples to assess nitrate distribution in these older areas. Inputs from individual systems should be similar regardless of age. Consequently, age of development should not be a factor affecting nitrate concentrations under unsewered areas unless plumes have not stabilized. We conclude, therefore, that plumes have not yet stabilized in areas developed since about 1980.

Parameter	Unsewered	Sewered
Alkalinity (ug/L)	148000	96000
Ammonia (ug/L)	75	73

Boron (ug/L)	15	13
Calcium (ug/L)	60306	35301
Chloride (ug/L)	12450	13970
Dissolved organic carbon (ug/L)	3100*	2125
Dissolved Oxygen (ug/L)	4330	3330
Eh (mV)	259	270
Iron (ug/L)	72	62
Magnesium (ug/L)	12033	7746
Manganese (ug/L)	205	131
Nitrate (ug/L)	1980*	778
pH	7.37*	6.99
Phosphorus (ug/L)	34	35
Potassium (ug/L)	1493	839
Sodium (ug/L)	7341	6105
Specific conductance (umhos/cm)	444	286
Sulfate (ug/L)	2725	2365
Temperature (^{o}C)	11.2	13.3
Total Kjeldahl nitrogen (ug/L)	440	323
Total organic carbon (ug/L)	3550*	2400
Zinc (ug/L)	6.6	3.8

Table 4 : Median chemical concentration from geoprobe samples in sewered and unsewered areas. An "*" indicates concentrations that differed between sewered and unsewered areas (at the 0.05 significance level).
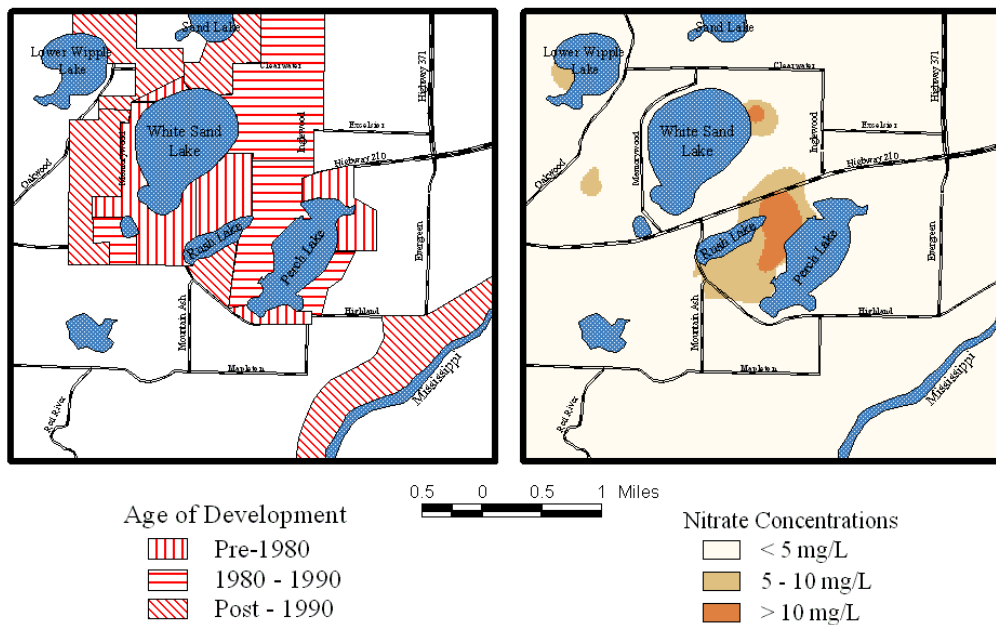

Figure 4: Age of development and distribution of nitrate across the study area.

The median nitrate concentration of 1980 ug/L is lower than concentrations found in other unsewered areas (Anderson et al., 1987; Baumann and Schafer, 1984; Hantzsche and Finnemore, 1992; Miller; MPCA 1998c; Quan et al., 1974; Tinker, 1991). There may be several reasons for this. First, ground water flow paths through unsewered subdivisions are relatively short. Tinker (1991) observed nitrate concentrations of approximately 1000 ug/L at the upgradient edge of an unsewered subdivision, compared to concentrations greater than 10000 ug/L at the down-gradient edge. The subdivisions in the Baxter area cluster around lakes and do not cover large geographical areas. Second, Miller observed increasing nitrate concentrations with increasing age of the subdivision. In Baxter, expansion of unsewered subdivisions has not occurred uniformly. Much of the development in the area has occurred since 1990 and most since 1980 (Figure 4). Third, there is lake water seepage to the aquifer from late summer through winter. This may dilute ground water nitrate concentrations on down-gradient sides of the lakes. Fourth, systems with the saturated zone near the bottom of the treatment system will not contribute significant amounts of nitrate to ground water because they remain anaerobic. Information from Phase 2, however, suggests that systems are contributing quantities of nitrate similar to concentrations found in the literature. Fifth, geochemical conditions within the aquifer may not support high nitrate concentrations. This is not supported by the data, however, which show a median Eh of 265 mV and a median dissolved oxygen content of 4300 mg/L at the water table. Nitrate will be stable under these geochemical conditions. Finally, nitrogen inputs may be less in Baxter than in other unsewered areas because of reduced inputs from individual systems or increased lot size compared to other unsewered areas. Concentrations of nitrate in individual plumes, however, are similar to concentrations found in other studies. We conclude that nitrate concentrations are relatively low compared to other unsewered areas primarily because the area is small in geopgraphic extent. Dilution from lake outflow and the young age of development also contribute to the low nitrate concentrations.

Nitrate concentrations in geoprobe samples were not correlated with concentrations of any other chemical. Consequently, nitrate concentrations in the upper

few feet of the aquifer are directly related to nitrogen inputs. Organic carbon, which was higher in unsewered areas, was correlated with concentrations of ammonia ($R^2 = 0.492$) and Kjeldahl nitrogen ($R^2 = 0.804$). Septic systems are a potential source of reduced nitrogen and organic carbon when the seasonal high water table is close to the bottom of treatment system.

Median values for specific conductance, pH, Eh, and for concentrations of chloride, nitrate, dissolved oxygen, and iron for different sampling depths are illustrated in Table 5. Mann-Whitney tests indicate no significant differences in any sampled parameter between shallow and deep geoprobe samples. Median values for pH, Eh, and for concentrations of chloride, nitrate, dissolved oxygen, and iron differed between the shallow temporary wells and deeper domestic wells, however. There are significant changes in geochemistry at depths of 20 feet or more within the aquifer. Oxygen and nitrate concentrations decrease, Eh decreases, and iron and manganese concentrations increase with depth. Figure 5 illustrates the presence of an oxygenated zone to a depth of about 20 feet in the aquifer. The general pattern of decreasing oxygen and nitrate with depth is similar to results for St. Cloud (MPCA, 1998c), although the thickness of the oxygenated zone was less than 10 feet in St. Cloud. Chloride distribution and tritium sampling from the St. Cloud study indicate post-1953 water extends deeply (up to 80 feet) into surficial aquifers. Since nitrate is mobile but not found below 20 feet, denitrification most likely accounts for the loss of nitrate with depth. The change in geochemical conditions at some depth was abrupt for both the St. Cloud and Baxter studies.

Parameter	Geoprobe < 5 feet below water table	Geoprobe > 5 feet below water table	Wells < 30 feet deep	Wells > 30 feet deep
Chloride (ug/L)	12500 b	19700 ab	28000 a	17000 ab
Dissolved oxygen (ug/L)	3330 ab	6050 a	1870 b	390 c
Eh (mV)	249 a	270 a	316 a	77 b
Iron (ug/L)	77 b	47 b	200 b	3700 a
Nitrate (ug/L)	950 a	780 ab	700 ab	< 100 b
pH	7.22 b	7080 b	7.90 a	7.50 a
Specific Conductance (umhos/cm)	418	286	223	281

Table 5 : Median chemical concentrations for different sampling depths. Different letters within a row indicate concentrations that differed at a significance level of 0.05.
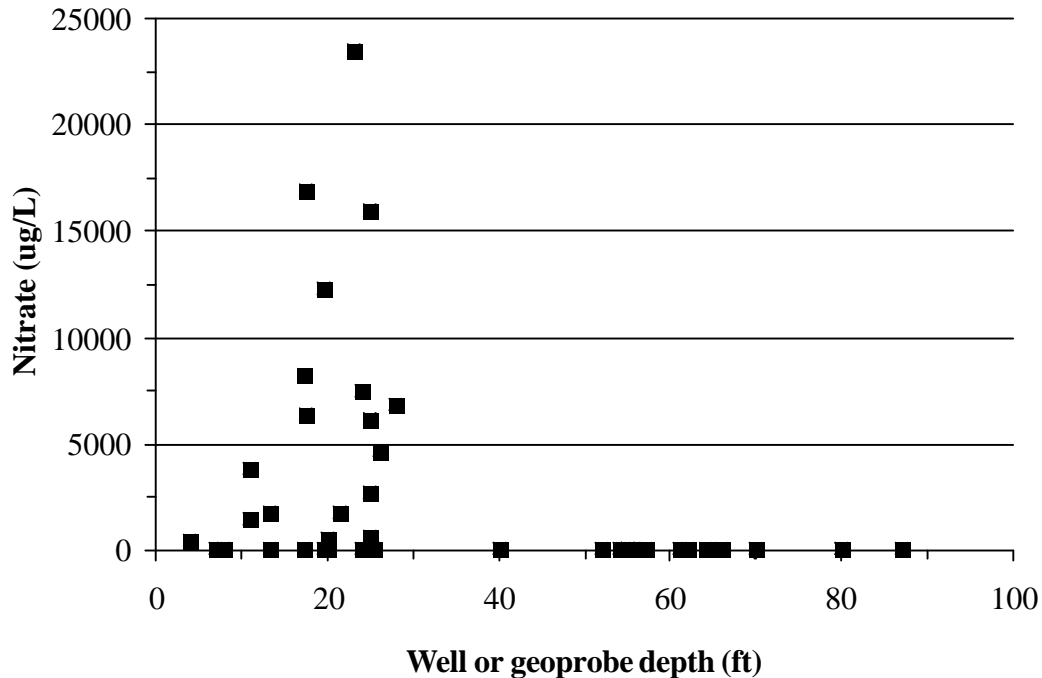
Figure 5 : Nitrate concentrations as a function of well or geoprobe depth.

Considering samples from domestic wells, nitrate was negatively correlated with well depth (R^2 = -0.449) and positively correlated with oxidation-reduction potential (R^2 = 0.385). These are not particularly strong correlations, but they reflect the decrease in nitrate concentrations with depth in the aquifer. The lack of correlations for nitrate in geoprobe samples indicates concentrations of nitrate in the upper portion of the aquifer are controlled by inputs at the top of the aquifer. Unless suitable conditions for denitrification exist within the aquifer, as occur below about 20 feet in the aquifer underlying the study area, nitrate is conservative in ground water.

Phase 2

The discussion of results for Phase 2 is divided into sections on inorganic chemicals, bacteria, and Volatile Organic Compounds (VOCs).

Inorganic Chemicals

Septic tank effluent is reducing, with high concentrations of iron, ammonia, Kjeldahl nitrogen, and low concentrations of nitrate (Table 6). Calcium and magnesium concentrations were low at Site 8 compared to other sites, while sodium, nickel, copper, zinc, iron, aluminum, and lead concentrations were high. Concentrations of zinc, aluminum, and lead at site 8 are at levels of potential concern if effluent reaches ground water. Site 4 also had high concentrations of most chemicals. Concentrations of magnesium, bicarbonate, calcium, ammonia, sulfate, and total phosphorus were similar among the seven sites. Concentrations of total organic carbon, chloride, aluminum, boron, fluoride, iron, nitrate, sodium, total Kjeldahl nitrogen, and zinc differed between sites.

Median effluent concentrations for all chemicals are within the range found in the literature (Table 7). Orthophosphate and ammonia in septic tanks accounted for about 80 and 40% of the total phosphorus and nitrogen, respectively. Wilhelm et al. (1994) and Brown (1980) report that most phosphorus and nitrogen go into tanks in organic forms, but that orthophosphate and ammonia account for about 80 and 50% of the total phosphorus and nitrogen in the tank effluent, respectively.

Chemical	Site 1	Site 2	Site 3	Site 5	Site 6	Site 7	Site 8
Alkalinity	-	432000	260000	461000	315000	-	443000
Aluminum	< 50	< 50	55	559	< 50	160	7936
Ammonia	59850	41880	22280	51590	65780	31600	73790
Boron	944	68	13248	76	470	55	763
Bromide	< 200	< 200	< 200	< 200	< 200	-	< 200
Cadmium	< 1.5	< 1.5	< 1.5	< 1.5	< 1.5	< 1.5	2.4
Calcium	34746	60669	60323	82272	50983	101470	69277
Chloride	45720	365200	31840	46730	54540	1140910	701140
Chromium	3.1	9.9	3.0	3.8	4.2	< 3.1	9.2
Copper	< 5.5	< 5.5	18	< 5.5	12	20	80
Fluoride	< 200	< 200	1020	< 200	< 200	100	1200
Iron	282	94	140	2064	725	257	17153
Lead	< 25	< 25	< 25	< 25	< 25	< 25	51
Magnesium	7125	45657	13936	17637	11558	20318	15603
Manganese	103	74	101	760	282	942	414
Nickel	< 6.0	< 6.0	< 6.0	< 6.0	< 6.0	< 6.0	13
Nitrate	30	10	20	50	50	1060	20
Orthophosphate	7150	90	4120	8100	10640	-	12030
Potassium	13450	981	11636	17958	19231	10649	23743
Sodium	103810	19119	42693	88613	49784	645480	466450
Sulfate-S	1300	350	200	3160	1220	510	570
Total Kjeldahl nitrogen	67440	630	32280	72170	113080	41100	119310

Total organic carbon	92600	299600	2900	-	162900	54700	271500
Total Phosphorus	7149	6309	6202	10465	10984	6546	19104
Zinc	12	7.7	63	389	48	256	1597

Table 6 : Concentrations of chemicals in septic tank effluent. Concentrations are in ug/L.

There were a large number of correlations between concentrations of different chemicals in septic tanks. Metal concentrations were often correlated, including lead with cadmium (R^2 = 1.000), cadmium with nickel (R^2 = 1.000), and aluminum with zinc (R^2 = 0.845). This is primarily due to a large number of non-detections for these metals, however. Most of the remaining significant correlations were between chemicals typically found at elevated concentrations in septic tank effluent. Examples include ammonia with potassium (R^2 = 0.941) and sodium (R^2 = 0.824).

Median concentrations of bicarbonate, boron, ammonia, chloride, iron, sodium, orthophosphate, and total organic carbon were higher in septic effluent compared to background concentrations in the aquifer (Table 8). Concentrations of nitrate and sulfate

Chemical	Robertson et al., 1991	Harmon et al., 1996	Robertson et al., 1991	This study
Alkalinity	365000	802000	316000	432000
Ammonia	30000	128000	59000	55720
Calcium	40000	137000	14000	60496
Chloride	45000	207000	55000	50635
Dissolved organic carbon	37000	19200	50000	10800
Magnesium	14000	25000	3000	14769
Nitrate	1000	< 100	100	25
Phosphate	8000	9000	13000	7625
Potassium	12000	43000	21000	15704
Sodium	98000	107000	90000	69198
Sulfate-S	27000	59000	42000	895
Total Kjeldahl nitrogen	-	152000	-	69805

Table 7 : Comparison of chemical concentrations in septic tanks from different studies. Concentrations are in ug/L.

were lower in the tank effluent compared to background concentrations in the aquifer. Approximately 80 percent of ammonia nitrogen was converted to nitrate in the unsaturated zone beneath the drainfield. Within individual systems, the percentage of

ammonia converted to nitrate ranged from 37 to 100 percent. This compares with values of 70 to 100 percent reported in the literature (Brown, 1980; Gold et al., 1992).

Bicarbonate, nitrogen, boron, iron, sodium, phosphate, and organic carbon are potential contaminants of ground water because concentrations in septic tank effluent are higher than background concentrations in the aquifer. Median concentrations of boron, ammonia, chloride, sodium, phosphorus, and nitrate were higher directly below the drainfield compared to background concentrations (Table 9). These are chemicals that may increase in concentration in ground water under unsewered areas compared to background concentrations. Consequently, these represent potential chemicals of concern in unsewered residential areas of Baxter.

Chemical	Maximum in plume	Tank	Background
Alkalinity	22000	432000	130000
Aluminum	< 49.9	< 49.9	< 49.9
Ammonia-nitrogen	60	55720	55
Boron	267	616	33
Bromide	< 200	< 200	< 200
Cadmium	< 1.5	< 1.5	< 1.5
Calcium	45749	60496	46722
Chloride	107485	50635	20130
Chromium	< 3.1	6.7	4.1
Copper	5.5	< 5.1	5.8
Dissolved organic carbon	6400	10800	2100
Dissolved oxygen	1815	-	2600
Fluoride	-	< 200	-
Iron	228	1395	75
Lead	-	< 24.5	-
Magnesium	11584	14769	9910
Manganese	65	348	103
Nickel	13	< 6.0	5.7
Nitrate	43435	25	2065
Orthophosphate	2275	7625	30
Oxidation-reduction potential	104	52	67
pH	6.37	6.94	6.89

Phosphorus	4423	7625	58
Potassium	13204	15704	4687
Sodium	145066	69198	12216
Specific conductance	1134	616	343
Sulfate-S	9250	895	4135
Temperature	13.6	15.0	11.6
Total Kjeldahl nitrogen	775	69805	585
Total organic carbon	6850	271500	3350
Zinc	9.8	30	7.4

Table 8 : Comparison of median chemical concentrations in septic tanks, maximum concentrations found in ground water plumes, and background concentrations. Data from all sites was pooled for the analysis. Concentrations are in ug/L except pH, specific conductance (umhos/cm), temperature (^{o}C), and oxidation-reduction potential (mV).

Chemical	1	2	3	5	6	7	8
Alkalinity	301000	190000	-	45000	301000	-	26000
Alkalinity (lab)	-	234000	379000	22000	282000	-	432000
Aluminum	< 50	504	< 50	154	404	84	82
Ammonia	60	70	580	3110	8260	360	1360
Boron	89	432	4924	70	313	195	1614
Bromide	< 200	< 200	< 200	< 200	< 200	-	< 200
Cadmium	< 1.5	< 1.5	< 1.5	< 1.5	< 1.5	2.4	< 1.5
Calcium	102760	90352	119920	48203	104600	106140	116210
Chloride	360580	651860	91620	57460	285130	313240	651860
Chromium	50	5.1	8.7	7.7	5.1	4.0	9.9
Copper	7.1	8.6	16.3	21.3	6.6	5.6	13
Dissolved organic carbon	-	7900	13200	15100	9200	5100	10800
Dissolved oxygen	18200	8760	15280	3880	2590	3810	8760
Fluoride	< 200	< 200	590	< 200	< 200	< 200	540
Iron	302	344	3181	876	233	278	325
Lead	< 24.5	< 24.5	< 24.5	< 24.5	< 24.5	< 24.5	< 24.5
Magnesium	16522	21681	38526	14038	24180	17320	45657
Manganese	2091	979	812	1499	800	546	678
Nickel	81	14	60	22	16	149	19
Nitrate	22140	54420	24500	51430	36530	16540	54420
Orthophosphate	990	550	3520	1040	5140	-	5030
Oxidation-reduction potential	697	347	82	152	107	119	152

pH	8.25	7.83	7.38	7.00	8.08	7.71	7.90
Phosphorus	872	5110	4234	1103	5153	72	5110
Potassium	5053	23743	13252	16449	16290	21861	20674
Sodium	296210	412980	81252	70143	129210	78134	412980
Specific conductance	2260	2576	1069	761	1242	10840	2576
Sulfate-S	17560	7910	9910	11230	15140	17400	7460
Temperature	11.9	14.9	19.0	13.9	12.4	11.6	14.0
Total Kjeldahl nitrogen	1010	930	7170	4070	970	1410	2330
Total organic carbon	14000	12600	126500	18800	13000	12500	13100
Total phosphorus	870	300	40	-	60	-	10
Zinc	35	18	24	55	31	18	25

Table 9 : Maximum concentrations observed in plumes for each site.

Ammonia-nitrogen within each plume down-gradient of the drainfields did not exceed background concentrations. Ammonia-nitrogen can thus be eliminated as a chemical of potential concern in unsewered areas of Baxter. The maximum concentrations of nitrate down-gradient of the septic drainfields exceeded the drinking water criteria (Health Risk Limit or HRL) of 10000 ug/L at all sites (Table 9). Maximum concentrations ranged from 22140 to 54420 ug/L. These concentrations are similar to values found in the literature (Robertson et al., 1991; Harmson et al., 1996; Wilhelm et al., 1994; and Walker et al., 1973). The health-based criterion of 1000 ug/L for manganese differs from the current HRL of 100 ug/L (Minnesota Department of Health, 1997). The value of 1000 ug/L was exceeded at two sites. Secondary Maximum Contaminant Levels were exceeded for aluminum, chloride, and iron at four, four, and five sites, respectively. Septic systems increase the risk of exceeding drinking criteria for nitrate and chloride. Elevated concentrations of aluminum, iron, and manganese cannot be attributed to septic systems because there was no difference in concentrations between septic systems and background for these chemicals.

Boron was the only chemical for which concentrations in the septic tank were correlated with the concentration beneath the drainfield. Concentrations of nitrate beneath the drainfield did not correlate with ammonia concentrations in the septic tank. These results are surprising, since higher concentrations in the tank should result in higher concentrations in ground water for conservative chemicals such as chloride and nitrate. The data indicate rates of nitrification vary beneath different septic systems.

A plume is the portion of ground water impacted by a septic system. Chloride concentrations two or more times greater than background concentrations represented a sample collected from a septic plume. Plume travel distances are illustrated in Table 10 for boron, nitrate, chloride, phosphorus, and sodium. Plume lengths, as indicated by elevated chloride concentrations, were less than 15 meters at Sites 3, 6, and 8 and more than 140 meters at Site 5. Using static water elevations from field measurements, the head gradient in the aquifer was about 0.002 m/m. Assuming a conductivity of 1.5 meters per day and a porosity of 0.25 cm^3/cm^3, the estimated time for chloride to move 140 meters is about 32 years. The septic system at Site 5 is more than 20 years old but less than 30 years old, so it is possible this plume has not yet stabilized. Sodium attenuated slowly within the aquifer, while boron was attenuated only at Site 5. Lee and Bennett (1998) demonstrate that boron is a good indicator of septic tank inputs to ground water, since concentrations of boron in effluent are higher than background concentrations in ground water and because boron is fairly conservative in ground water. Phosphorus moved less than 12 meters at all sites.

Data from other studies indicate plume lengths of 30 to 130 meters (Robertson et al., 1991; Harman et al., 1996; Wilhelm et al., 1994; and Walker et al., 1973). Nitrate is conservative in most studies. Elevated phosphorus concentrations rarely exceed 15 meters in length within the plume, and are generally less than 5 meters in length (Wilhelm et al., 1994; Reneau and Pettry, 1976; Rea and Upchurch, 1980).

Site	Chloride	Boron	Nitrate	Sodium	Phosphorus
			meters		
1	> 50	30	45	40	12
2	40	40	40	40	< 5
3	9	9	9	9	5
5	140	75	110	80	10
6	15	15	15	11	12
7	35	15	30	25	< 5
8	13	13	13	11	5

Table 10 : Down-gradient distance from the drainfield at which chemical concentrations approached background concentrations.

Phosphorus is an important chemical of concern in northern Minnesota. Lakes in this part of the state have recreational value that can be easily diminished with excessive inputs of phosphorus. There were no differences in phosphorus concentrations in ground water under sewered and unsewered areas (Table 4) despite very high phosphorus concentrations in septic tank effluent (Table 6). Phosphorus in ground water traveled less than 12 meters from the drainfield at all seven sites, and traveled five or fewer meters at sites 2, 3, 7, and 8. Phosphorus in the septic plumes sampled in this study has not traveled far enough to reach lakes. Additional investigations should include studies of plume stability, phosphorus movement in areas with a large number of nonconforming systems, and phosphorus movement in low pH and low buffering capacity environments.

Nitrate remained above background concentrations for the entire length of each plume, except at Sites 5 and 7 (Table 10). The ratio of nitrate to chloride is an indicator of nitrate attenuation, since chloride is conservative and should decrease in concentration only by dilution. Nitrate to chloride ratios in the plume decreased at all sites. Maximum and minimum ratios for each site are illustrated in Table 11. The average background ratio in the aquifer was 0.07 for all sites combined. The data in Tables 10 and 11 indicate nitrate is being attenuated within the plume. If dilution were the only mechanism of dilution, the ratio would decrease slowly. The rapid decrease in the ratio indicates nitrate is being consumed by microbes through denitrification, is taken up by plants, or is attenuated through anion adsorption. The mechanism of nitrate loss is unclear. Aravena and Robertson (1998) observed that about 30% of nitrate loss was attributable to oxidation of reduced sulfur, with the remaining 70% due to oxidation of organic carbon. Steinheimer et al. (1998) attributed nitrate loss to autotrophic denitrification in a loess soil, with ferrous iron being the electron donor.

Site	Maximum NO_3:Cl ratio	Minimum NO_3:Cl ratio
3	0.58	< 0.03
5	1.04	0.01
6	1.23	0.06
7	0.33	0.04
8	1.23	0.05

Table 11 : Nitrate to chloride ratios in septic plumes.

Results indicate nitrate is the primary inorganic chemical of concern associated with septic systems. Management of ground water quality in unsewered areas must therefore focus on nitrate. If nitrate is being attenuated within septic plumes, data in Table 9 provides an estimate of approximate nitrate plume lengths in Baxter. For a nitrate plume that is 100 meters in length from a septic system located on a one acre lot, and assuming a horizontal dispersivity of 0.1, 7.3 percent of the upper portion of the aquifer under that lot would have nitrate concentrations in excess of the drinking water criteria. With a lot size of 2.5 acres, this percentage decreases to 2.9 percent. The percentage of exceedances observed in this study is 25, considerably higher than the calculated rates. There are several factors that may contribute to the high rate of exceedance. First, sampling may have been biased toward intercepting septic plumes since samples were collected where access could be easily obtained. These are areas where septic systems will be located. Second, the average lot size in Baxter may be less than one acre. Even with a lot size of one-half acre, however, the exceedance rate would be only 14.6 percent. Third, there may be other nitrogen inputs, such as lawn fertilizers. These were not measured. Finally, the plumes sampled during this study may not be representative of plumes in the remaining unsewered areas of Baxter. Two factors may account for this. First, dilution of the plumes occurs from lake discharge during certain times of the year. Second, denitrification occurs in riparian zones along the lakeshore. Five of the sampled plumes were located along Perch Lake, which has an extensive riparian buffer and discharges to ground water during late summer.

Figure 6 illustrates concentrations of nitrate along the plume at site 5. The plume length was estimated by measuring the distance over which chloride concentrations remained more than two times greater than the background concentration. Curves for boron and chloride were similar, as would be expected since these are anions that are generally attenuated only through dilution with recharge water. The nitrate plume extends vertically to about 10 meters below the soil treatment system. The plume then appears to move primarily in a lateral direction, although the information collected is insufficient to verify this. A similar plume shape is evident for total phosphorus (Figure 7). The

phosphorus plume does not extend as deeply into the aquifer and is attenuated within about 12 meters of the soil treatment system. The shape of these plumes is similar to those observed in other studies (Robertson, 1995; Robertson and Blowes, 1995; Robertson et al., 1991).
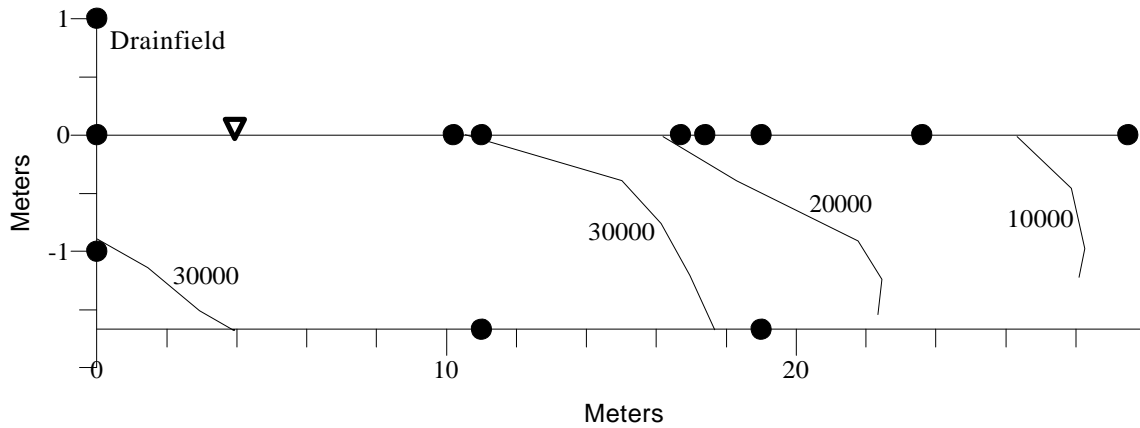
Figure 6 : Nitrate concentration, in ug/L, in the septic plume at site 5. Filled circles represent sampling locations.
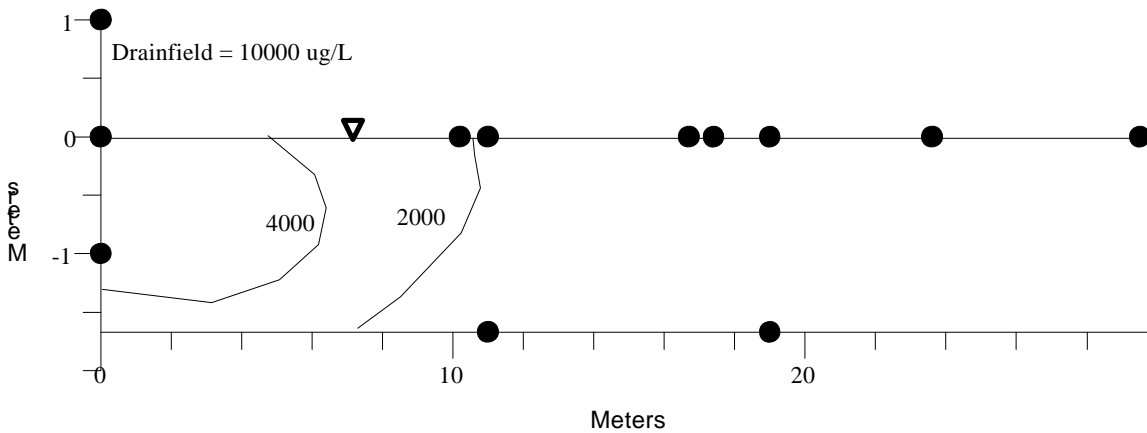
Figure 7 : Total phosphorus concentration, in ug/L, in the septic plume at site 5. Filled circles represent sampling locations.

Bacteria

Most probable number (MPN) concentrations of total coliform bacteria in septic effluent exceeded 200 per 100-mL at all seven sites, with concentrations greater than 240000 per 100-mL at site 2. Reneau (1978) and DeBorde et al. (1998) observed concentrations for total coliform bacteria of about 500000 per 100-mL. Concentrations of

total coliform bacteria in effluent, the number of detections and non-detections, and concentration ranges in ground water are summarized in Table 12. Concentrations in ground water decrease rapidly from about 200 per 100-mL to less than 1 per 100-mL within 10 meters of the drainfield (Figure 8). Hagedorn et al. (1978) observed a decrease in total bacteria of more than two orders of magnitude within 15 meters of the drainfield. They also observed, however, that the greatest movement of bacteria from the drainfield down-gradient in the septic plume followed precipitation events. Bacteria always reached 3 meters and sometimes 5 meters within 24 hours of a rain event. Brown (1980) observed a flushing of bacteria through the biomat and underlying soil following rainfall, but bacteria survival in groundwater was less than 100 days. The current study provides a best-case scenario with respect to bacteria in ground water, since the period of sampling was relatively dry. Although bacteria concentrations in ground water are low, the presence of bacteria indicates additional sampling may be warranted to determine if there are temporal variations in population. To accomplish this objective, a monitoring network would need to be established around one or more septic systems and the network sampled periodically to determine temporal variability in bacteria populations.

Site	Septic tank effluent concentrations (MPN/100-mL)	Ground Water		
		No. of non-detections	No. of detections	Range in concentration (MPN/100-mL)
1	> 2000	3	4	1 to 200
2	> 200	1	10	1 to 140
3	> 2400	3	6	1 to 11
5	> 200	5	6	1 to 120
6	> 200	3	5	1 to >2000
7	> 240000	2	6	1 to 200
8	> 200	11	4	1 to 12

Table 12 : Summary information for total bacteria found in septic effluent and ground water down-gradient of individual septic systems.
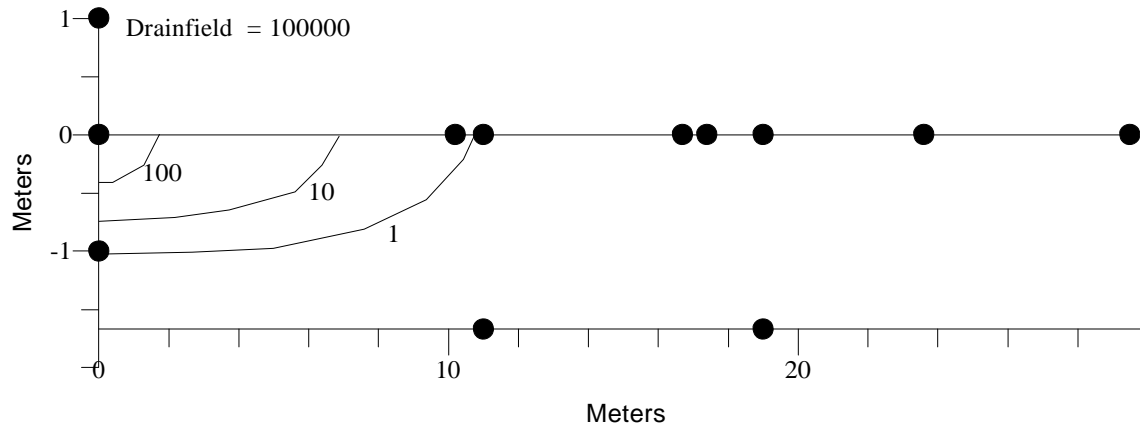
Figure 8 : Concentrations of total coliform bacteria, in MPN/100-ml, in the plume at site 5.

There were no detections of *E. Coli* in ground water at any site, except for a single detection of 2 per 100-mL at site 7. MPN concentrations in septic effluent were greater than 200 per 100-mL at all six sites, and appear to be greater than 2000 per 100-mL (Table 13). Reneau (1978) observed MPN concentrations of greater than 50000 per 100-mL.

Site	*E. coli* (MPN/100-mL)
1	> 200
2	2500
3	> 200
5	> 200
6	> 200
7	> 2400
8	> 2000

Table 13: Concentrations of *E. Coli* in septic tank effluent.

Although bacterial populations are low in the study, some research indicates viruses may be more persistent and travel farther than bacteria (Brown, 1980; DeBorde et al., 1998). Viruses generally represent a greater health risk to humans than bacteria. DeBorde et al. (1998) discuss some of the difficulties in sampling for viruses, including determining which viruses to sample for, high costs of sampling, and poor correlations

between bacteria and virus populations. Considering results of this study, it would be useful to sample for viruses in septic effluent and in the sample closest to the drainfield.

Volatile Organic Compounds (VOCs)

Septic effluent contained VOCs at each site. Table 14 summarizes total VOC concentrations and the number of VOC detections in septic effluent. There was considerable variability in the number of detections, with three or fewer detections at sites 2, 3, 5, 6, and 8, but 11 and 7 detections at sites 1 and 7, respectively. Total concentrations of VOCs did not correlate with the number of detections. The highest total VOC concentrations were at sites 5 and 6, even though just one and two VOCs were detected in effluent at these sites.

Site	Total VOCs (ug/L)	No. VOCs detected
1	168	11
2	245	2
3	305	3
5	800	1
6	610	2
7	138	7
8	297	2

Table 14 : Total concentration of VOCs in septic tank effluent and number of compounds detected.

Toluene was the most commonly detected VOC in septic tank effluent, being found in 7 samples at concentrations ranging from 7 to 800 ug/L (Table 15). Substituted benzenes accounted for two-thirds of the total detections in effluent. These are commonly found in fuel oils, gasoline, paints, paint thinners, varnishes, and other solvents commonly used in households. No VOC in ground water exceeded a drinking water standard.

Chemical	No. of detections	Concentration range (ug/L)
Toluene	7	7 to 800
Xylene	4	0.2 to 0.8
Methyl isobutyl ketone	4	7.3 to 220
Chemical	**No. of detections**	**Concentration range (ug/L)**
Chloroform	4	0.1 to 0.5

n-Butyl benzene	3	2.5 to 39
p-Isopropyl toluene	3	6.2 to 76
n-Propylbenzene	2	1.1 to 2.7
1,3,5-Trimethylbenzene	2	1.4 to 24
Acetone	2	30 to 290
Naphthalene	2	1.2 to 2
sec-Butylbenzene	2	0.8 to 1.8
tert-Butylbenzene	1	10
1,2,4-Trichlorobenzene	1	0.8
1,4-Dichlorobenzene	1	13
Ethylbenzene	1	0.3
Methylene chloride	1	0.5
1,2,4-Trimethylbenzene	1	12

Table 15 : VOCs detected and concentration range in septic tank effluent.

Thirteen VOC detections occurred in ground water. Eleven of these were chloroform at concentrations ranging from 0.1 to 2.6 ug/L. Chloroform may be naturally occurring, particularly in septic effluent, which has high concentrations of organic matter and chloride. There was one detection of chloroethane at a concentration of 6 ug/L, and a detection of methylene chloride at 1 ug/L. These chemicals are used in some household products, but not to the extent they once were.

Although there were 35 detections of nonhalogenated VOCs in effluent, there were no detections of these compounds in ground water. Non-halogenated VOCs are degraded in the presence of oxygen. The results indicate VOCs are attenuated within septic drainfields. VOCs associated with septic systems do not represent a health concern despite their presence in septic waste.

Conclusions and Recommendations

Results from Phase 1 of the Baxter study indicates higher pH and concentrations of nitrate, total organic carbon, and dissolved organic carbon in unsewered areas compared to sewered areas. Since nitrate concentration in the upper 10 feet of the aquifer was not correlated with any parameter, differences in nitrate concentrations between sewered and unsewered areas are due to greater nitrogen inputs in unsewered areas. Concentrations of nitrate under unsewered areas in Baxter are less than concentrations under unsewered areas described in the literature. Concentrations of most chemicals in septic tanks and plumes were similar to concentrations found in the literature. Therefore, the most likely reason for the lower concentrations of nitrate is that unsewered developments are small in geographic extent compared to other studies in the literature. Although nitrate concentrations in this study were low compared to other studies, 25 percent of sampled geoprobes exceeded the drinking water criteria for nitrate.

Concentrations of nitrate decrease when ground water conditions become favorable for denitrification. Considering all well and geoprobe samples, nitrate concentration decreased with increasing well depth and with decreasing Eh (oxidation-reduction potential). Nitrate was detected in samples collected from the upper 20 feet of the aquifer, but not in any sample below that depth. There appears to be a zone between 10 and 20 feet where denitrification rapidly occurs. This denitrification zone is somewhat deeper than observed in the St. Cloud land use study. Denitrification also appears to occur in riparian zones along the lakes where sampling occurred.

The following general recommendations are based on the results of this study.

1. Additional Phase 1 investigations should be conducted in other areas. Age of development and lot size are two variables that need to be evaluated with respect to impacts of septic systems on ground water quality. Age of development may be an important factor if it takes several years for plumes to stabilize.

2. Additional plume investigations should focus on three areas of investigation. First is gaining an understanding of the relationship between plumes and lake water quality. Plumes which discharge to lakes must be identified. Rather than track plumes from

the septic tank to a lake shore, plumes should be identified near the shore-lake interface. This may be accomplished by probing parallel to this interface until a plume is encountered. Second, greater effort needs to be made to determine the behavior of microbes originating in the septic tank. Sampling should be expanded to include viruses. A permanent monitoring network should be established in a plume where bacteria have been identified in ground water. Temporal factors are likely to be important for understanding the behavior and fate of microbes in ground water. Sampling should therefore occur following significant precipitation events. Third, hydrologic relationships need to be assessed within individual plumes. A permanent network should be established within a plume. Recharge measurements should be made using continuous water level measurements. Slug tests would be performed in each well. Chemical concentrations would be measured quarterly and after significant precipitation effects. The objective of this study would be to evaluate temporal variability in ground water quality within a plume.

The following recommendations are made for the Baxter area.

1. A phase 3 study should not be conducted in Baxter. Phase 3 is a long-term study of ground water quality following a change in land use, such as unsewered to sewered. Even though the Baxter area will be sewered over the next few years, nitrate concentrations are too low to easily evaluate changes in water quality.

2. If portions of Baxter remain unsewered, or if unsewered development continues in the city, management plans should be developed to minimize risk to drinking water receptors and lakes. Management strategies would include minimum lot sizes, setback distances from lakes, minimum depths for domestic wells, and pumping restrictions from the aquifer underlying unsewered areas. Engineering strategies also limit impacts from septic systems by providing better treatment of wastes. Engineering strategies include separating grey and black water, maintaining appropriate separation distances in the unsaturated zone, and advanced treatment of waste.

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