ground water

Assessing Background Ground Water Chemistry beneath a New Unsewered Subdivision

by Jeffrey D. Wilcox[1], Kenneth R. Bradbury[2], Curtis L. Thomas[2], and Jean M. Bahr[3]

Abstract

Previous site-specific studies designed to assess the impacts of unsewered subdivisions on ground water quality have relied on upgradient monitoring wells or very limited background data to characterize conditions prior to development. In this study, an extensive monitoring program was designed to document ground water conditions prior to construction of a rural subdivision in south-central Wisconsin. Previous agricultural land use has impacted ground water quality; concentrations of chloride, nitrate-nitrogen, and atrazine ranged from below the level of detection to 296 mg/L, 36 mg/L, and 0.8 μg/L, respectively, and were highly variable from well to well and through time. Seasonal variations in recharge, surface topography, aquifer heterogeneities, surficial loading patterns, and well casing depth explain observed variations in ground water chemistry. This variability would not have been detected if background conditions were determined from only a few monitoring wells or inferred from wells located upgradient of the subdivision site. This project demonstrates the importance of characterizing both ground water quality and chemical variability prior to land-use change to detect any changes once homes are constructed.

Introduction

Residential development of rural areas has become a significant land-use issue in many parts of the United States. Between 1999 and 2003, ~800,000 new single-unit residences were constructed beyond urban and suburban boundaries in the United States (U.S. Census Bureau 2004). Although residential developments near urban centers typically use city water and sewer services, rural developments often rely on private water supply wells and on-site waste water treatment systems. Almost 26 million of the estimated 121 million homes (21%) in the United States are served by on-site systems, including ~12 million of the 26 million homes (45%) located beyond urban and suburban boundaries (U.S. Census Bureau 2004). Local county or township officials are charged with regulating unsewered residential development, and regulation in some areas is driven by concerns about the impacts of development on ground water quality. On-site treatment of waste water can release contaminants such as nitrate, bacteria, viruses, and hazardous household chemicals to the subsurface (Canter and Knox 1985), posing potential threats to nearby wells and surface water. Assessing these potential threats and the overall impact of unsewered residential development on ground water quality should be of interest not only to the hydrogeologic community but also to public officials in charge of zoning and natural resource protection.

Previous studies have combined water quality and land-use data to draw conclusions about the effects of replacing agricultural land with unsewered subdivisions on local ground water quality (Gold et al. 1990; Goetz et al. 1991; Anderson 1993; Trojan et al. 2003). A limited number of site-specific field studies have documented ground water conditions beneath existing unsewered subdivisions (Tinker 1991; Shaw et al. 1993; Thomas 2000) and suggest that septic systems can sometimes impact ground water quality. However, none of these studies have benefited from the availability of a background water quality data set, and instead, either assumed minimal impacts

---

[1] Corresponding author: Department of Geology and Geophysics, University of Wisconsin—Madison, 1215 West Dayton Street, Madison, WI 53706; (608) 262-9467; fax (608) 262-0693; jwilcox@geology.wisc.edu

[2] Wisconsin Geological and Natural History Survey, University of Wisconsin—Extension, 3817 Mineral Point Rd., Madison, WI, 53705.

[3] Department of Geology and Geophysics, University of Wisconsin—Madison, 3817 Mineral Point Rd., Madison, WI, 53705.

Received May 2004, accepted December 2004.

doi: 10.1111/j.1745-6584.2005.00044.x

from previous land-use or inferred background conditions on the basis of upgradient monitoring wells. In a different study, five wells were drilled and sampled during subdivision construction in 1989 and sampled again 4 years later (Carleton and Vowinkel 1996). Initial sampling showed high nitrate concentrations as a result of previous agricultural land use. Nitrate concentrations decreased over the time period of the study, which the authors attribute to a decrease of nitrogen input during subdivision construction.

New unsewered subdivisions are often constructed on land formerly used for agriculture, where elevated concentrations of nitrate, chloride, phosphorus, and pesticide residues in ground water and surface water may have resulted from previous applications of fertilizers and pesticides (e.g., Saffigna and Keeney 1977; Bohlke and Denver 1995; Fuhrer et al. 1999). In addition to elevated concentrations of these constituents, there may be significant temporal and spatial variability in ground water chemistry beneath agricultural land (Anderson 1993; Hallberg and Keeney 1993; Kelly 1997; Landon et al. 2000; Delin and Landon 2002). In this study, an extensive background monitoring program was designed to document chemical variability in time and space for a full year prior to construction of a rural subdivision. In doing so, it tested the assumptions from previous studies that effects from former land uses are negligible, can be inferred by upgradient wells, or limited monitoring during the land-use change.

Site History

In the summer of 2001, a 31.7-ha (78 acre) parcel ~20 km from the city of Madison, Wisconsin, was chosen as the site for a new residential development (Figure 1). The final plat for a 30-home unsewered subdivision, named Savannah Valley, was approved in the summer of 2002. Site improvement began in September 2002, and construction of new homes began in early 2003. When selected for development, the site contained farmed and wooded areas as well as a small wetland. Its agricultural history dates back at least a century, with corn, soybeans, wheat, and hay as the dominant crops in recent years. The site has been fertilized with manure as recently as May 2002; the historical use of synthetic fertilizers is unknown. A drain tile beneath the center of the property (Figure 2) empties into a drainage ditch just north of the site. Overall, the site has rolling topography, with two glacial kames providing the greatest relief. The surrounding area is predominantly agricultural, although Drover's Woods, an existing 54-home unsewered subdivision, is located ~1.3 km to the east. Precipitation in the area averages almost 84 cm/year (Midwestern Regional Climate Center 2003).

Methods

Well Installation

A monitoring well network on the subdivision property allowed determination of the water table configuration and provided sampling points for monitoring ground water chemistry (Figure 1). Eleven water table wells were installed using hollow stem augers and were constructed of 5-cm, polyvinyl chloride (PVC) pipe with 1.5-m screened intervals. The tops of the screens were designed to be placed just below the water table, although the exact water table depth was not always evident during drilling. Slug tests were performed on the seven wells that were screened below the water table, and estimates of hydraulic conductivity were determined using the Hvorslev method (Fetter 1994). Eight additional wells were installed using Geoprobe "direct-push" technology (Geoprobe Systems, Salinas, Kansas) to monitor the effects of newly created drainage basins on recharge patterns and water quality and to characterize the southern portion of the property where drill rig access was difficult. These wells were constructed of 2.5-cm PVC pipe, with a 1.5-m screened interval placed just beneath the water table. Five deeper wells were installed into bedrock using mud rotary drilling. These 15-cm-diameter wells were constructed similarly to most potable water wells in the area, with 12 to

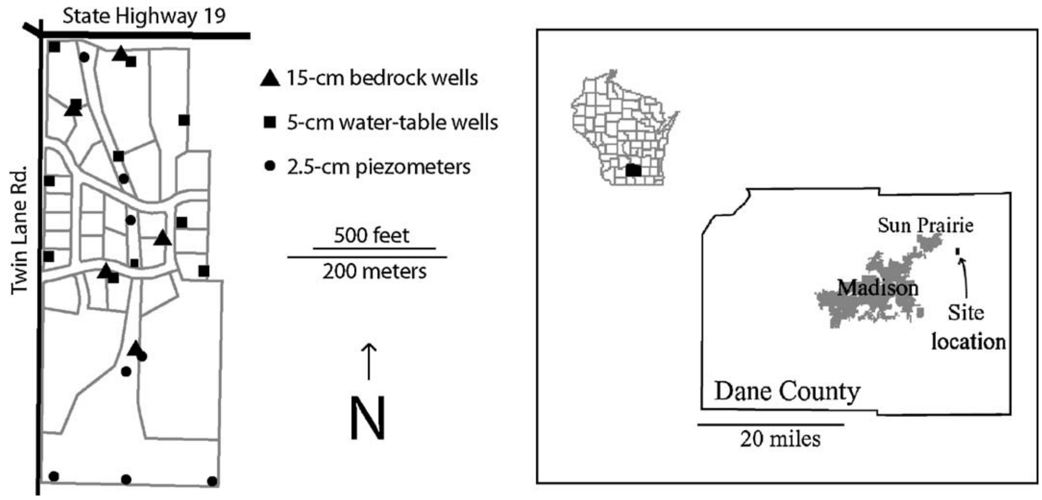


Figure 1. Location, layout, and monitoring well locations for the Savannah Valley subdivision site.

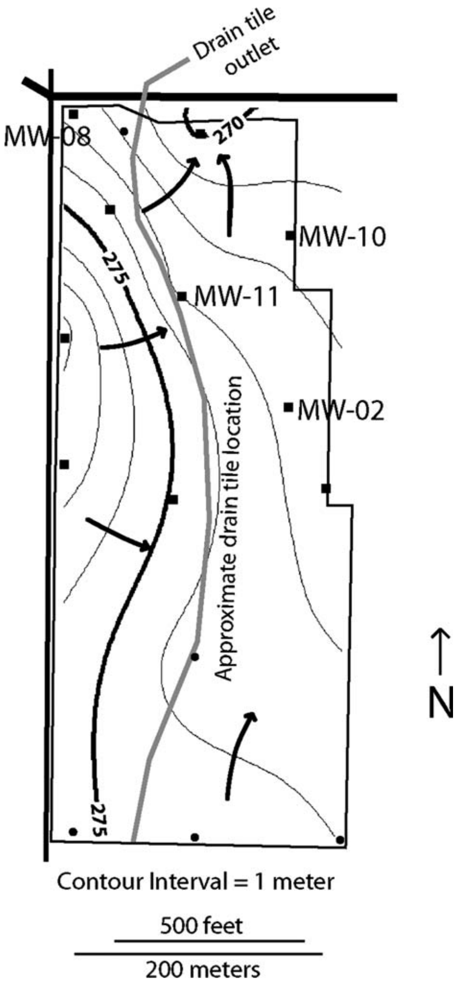


Figure 2. Water table map, December 20, 2002.

18 m (40 to 60 feet) of casing above a 12- to 30-m (40 to 100 feet) open interval. Additional wells used in the study included 18 existing residential wells, of which 8 are located in the Drovers Woods subdivision. The remaining wells provide potable water to farmers and other rural residents.

Sample Collection and Analysis

The existing residential wells were sampled at outdoor faucets prior to treatment by any water softeners. Sampling occurred after the temperature and conductivity of the running water stabilized or after the pump had turned on. Monitoring wells at the study site were sampled using bailers or submersible pumps. To avoid sampling stagnant water, at least three well volumes were removed from each monitoring well prior to sample collection.

Water temperature, conductivity, and pH were measured in the field prior to sample filtration. Water samples intended for chemical analyses were vacuum filtered through 0.45-µm nylon membranes. Samples intended for dissolved metal analyses were preserved with concentrated nitric acid, and all samples were kept on ice until they could be refrigerated. Field duplicates were collected on three occasions.

The University of Wisconsin Soil and Plant Analysis Laboratory analyzed samples for major ions using ion chromatography and inductively coupled plasma spectrometry. Laboratory-fortified blanks were analyzed with each set of samples, and instrument performance check solutions and calibration blanks were analyzed for every 10 samples. Alkalinity was measured by titration with hydrochloric acid according to Standard Method 2320B (American Public Health Association, American Water Works Association, and Water Environment Federation 1998), and concentrations of parent atrazine were analyzed at the Wisconsin State Laboratory of Hygiene in Madison using triazine immunoassay method T750ALT.

The University of Waterloo Environmental Isotope Laboratory analyzed seven ground water samples for the isotopic composition of nitrogen ($\delta^{15}N$) in dissolved inorganic nitrate. Samples collected for isotopic analyses were filtered, frozen, and shipped overnight to the lab. Isotope analyses have been used in a number of previous studies as a tool for identifying nitrate sources (Gormly and Spalding 1979; Kreitler and Browning 1983; Aravena et al. 1993; Komor and Anderson 1993; Fogg et al. 1998; Shanley et al. 1998). The basis of this method is that nitrate derived from different sources will have different $^{15}N/^{14}N$ ratios, which are reported as $\delta^{15}N$ with units of "per mill" (‰). In order to evaluate the suitability of this tool for the Savannah Valley subdivision project, samples were collected for nitrogen isotope analysis during a routine sampling round in October 2002.

Results

Hydrostratigraphy and Ground Water Flow

The site is characterized by a thin (0 to 1.5 m) silt-loam soil overlying a sequence of unlithified glacial sediments. The glacial unit is composed primarily of sandy gravel and interbedded sands and gravels, although finer sediments are also present. Grain size ranges from fine clays to erratic boulders >3 m in diameter. Pebbles and cobbles are predominantly dolomite, although smaller amounts of other rock types are also present. The glacial deposits cover >100 m of interbedded sandstones and dolomites of Ordovician and Cambrian age. The depth to bedrock across the site ranges from 6 m along the western ridge to ~20 m below the kames on the northern edge of the site.

Two aquifers are present at the site: a shallow unlithified aquifer composed of glacial sediment and a bedrock aquifer composed of the sedimentary units discussed previously. Water levels in site wells ranged from 2.1 to 16.5 m below the land surface. Static water levels obtained from local well construction reports suggest that regional ground water flow is from west to east. Local ground water flow converges toward a surface ditch just north of the site across Highway 19. The drain tile running beneath the site appears to have minimal impact on ground water flow, and the tile and connected drainage ditch were dry for much of the study period. The tile might affect ground water flow direction during wetter years when the water table is higher. However, during the course of this study, the configuration of the water table remained relatively constant (Figure 2).

Overall, ground water flow is relatively rapid through the glacial aquifer, with horizontal velocities on the order of 15 to 30 cm/d estimated on the basis of hydraulic conductivities measured via slug tests and a representative value of 0.30 for effective porosity in mixed sand and gravel (Fetter 1994). Hydrographs for water table wells show that most recharge in the unlithified aquifer occurs during the spring months, with declining water levels the rest of the year. During spring recharge, the aquifer responds rapidly to precipitation, snowmelt, and ground thaw, although the magnitude of this response varies with location (Figure 3). In 2002, the shallow aquifer received recharge from mid-February through mid-June; however, after an extremely dry winter, water levels did not begin to rise significantly in 2003 until May. Water level rise in the shallow bedrock aquifer occurred later and over a longer time than in the unlithified aquifer. Water levels in all monitoring wells were lower in early 2003 than they were at the same time in 2002, which is not surprising because the fall and winter of 2002 were much drier than in 2001.

Ground Water Chemistry

Background chemical data were collected for a full year before significant site improvements began in the fall of 2002. Selected water chemistry data collected from the four well sets are listed in Table 1. Isotope analyses revealed the $\delta^{15}N$ values of nitrate from seven sampled wells that ranged from +4.2‰ to +8.9‰, with a mean of +5.6‰ ± 1.7‰.

Discussion

The parameters of primary interest in this study are those commonly associated with domestic waste water, including nitrate, sodium, chloride, and conductivity. Almost all the water samples collected from shallow wells showed evidence of previous human impact on the basis of these constituents. Although highly variable, median concentrations measured in this study were higher than average values found in a survey of shallow ground water in the county (Dane County Regional Planning Commission [RPC] 1999) and median values beneath undeveloped forest or preservation areas in the Anoka Sand Plain in Minnesota (Trojan et al. 2003) (Table 2). Nitrate concentrations were consistent with other surveys in agricultural areas of Wisconsin (Saffigna and Keeney 1977; Chern et al. 1999) but were generally higher than 2 mg/L, which is frequently assumed to be the maximum concentration in natural ground water unaffected by anthropogenic sources (Hallberg and Keeney 1993).

Nitrogen Isotopes as a Tool for Distinguishing Nitrate Sources

Nitrogen isotope analyses were employed in an effort to identify the source of high background nitrate concentrations at the Savannah Valley subdivision site. Typical $\delta^{15}N$ values for animal waste nitrate and commercial fertilizers, the major past sources of nitrate at the subdivision site, are +10‰ to +20‰ and −2‰ to +4‰, respectively (Aravena et al. 1993). Nitrate derived from soil nitrogen has typical $\delta^{15}N$ values between +3‰ and +8‰ but is not likely to be a significant component of the nitrogen budget at this site. While denitrification can cause an increase in $\delta^{15}N$ in residual nitrate, high dissolved oxygen concentrations make it unlikely that this process is occurring in ground water sampled by the shallow monitoring wells.

Ground water nitrate beneath the subdivision site appears to have originated from both synthetic and organic (cow manure) fertilizers as the measured $\delta^{15}N$ values fall between the typical values for the two sources (Figure 4). However, the four wells with the highest nitrate concentrations (>10 mg/L as N) had the lowest $\delta^{15}N$ values, ranging from +4.2‰ to +5.2‰. These low $\delta^{15}N$ values suggest that the primary source for high background nitrate concentrations was synthetic fertilizer and not animal waste. Nitrate derived from human waste water should have higher $\delta^{15}N$ values (between +10 and +20), so nitrate sampled from any wells that are significantly

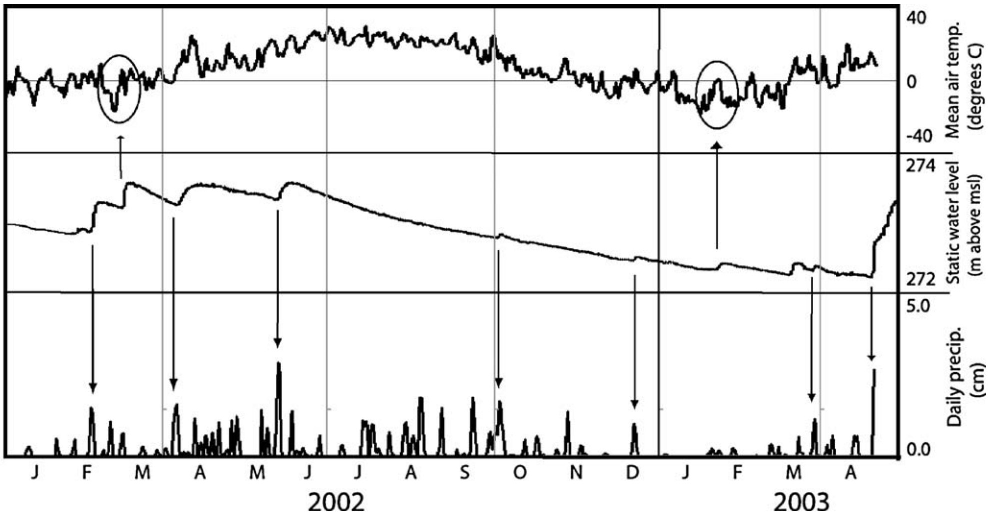


Figure 3. Hydrograph of monitoring well MW-08 (b), showing how warming temperatures during the spring thaw season (a) and large storm events (c) precede water level peaks.

Table 1
Selected Water Quality Data Prior to Construction of Homes at Savannah Valley, December 2001 to October 2002

Parameter	Number of Samples	Minimum	Maximum	Median	Average	Standard Deviation
Savannah Valley water table wells						
Nitrate[1]	65	<0.1	36.4	4.6	7.5	7.9
Chloride[2]	65	0.3	296.0	12.3	35.8	57.0
Sodium[2]	65	3.9	163.2	19.4	36.2	41.8
Atrazine[3]	11	<0.1	0.8	0.2	0.3	0.3
Conductivity[4]	65	531	1839	851	904	246
Savannah Valley bedrock wells						
Nitrate[1]	13	<0.1	12.6	4.2	5.0	3.8
Chloride[2]	13	1.5	70.0	14.1	22.5	21.5
Sodium[2]	13	3.6	34.9	12.9	16.4	10.8
Atrazine[3]	5	<0.1	0.3	0.3	0.2	0.1
Conductivity[4]	13	608	921	782	771	99
Drovers Woods subdivision residential bedrock wells						
Nitrate[1]	8	<0.1	8.8	7.3	6.3	2.9
Chloride[2]	8	0.3	35.9	19.7	19.4	11.3
Sodium[2]	8	4.4	20.7	11.3	12.9	5.8
Conductivity[3]	8	540	823	769	739	91
Rural residential bedrock wells						
Nitrate[1]	10	0.2	25.6	5.0	8.2	8.0
Chloride[2]	10	4.4	76.8	23.4	27.6	23.1
Sodium[2]	10	4.5	46.0	8.6	12.1	12.2
Conductivity[3]	10	664	1025	782	835	148

Concentrations are listed as: [1]mg/L nitrate-nitrogen, [2]mg/L and [3]µg/L parent compound, and [4]µS/cm at 25°C.

impacted by septic systems in the future should exhibit an upward shift in $\delta^{15}N$ values.

Controls on Variability in Chemical Composition

Significant temporal and spatial variability in ground water chemistry existed across the field site prior to subdivision construction. This variability can be explained by seasonal variations in recharge, surface topography, aquifer heterogeneities, surficial loading patterns, and well construction.

Table 2
Concentrations of Key Water Quality Parameters Were Higher in This Study Than in Surveys of Shallow Ground Water in the County (Dane County RPC 1999) and beneath Undeveloped Areas of the Anoka Sand Plain in Minnesota (Trojan et al. 2003)

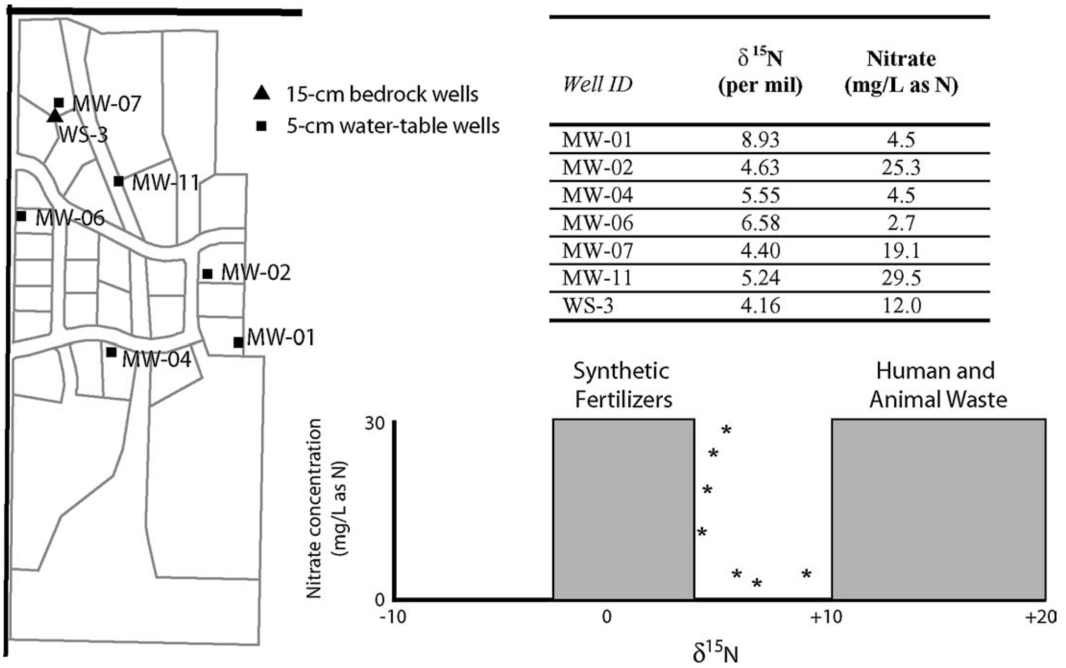
Parameter	This Study[1]	Dane County, Wisconsin[2]	Anoka Sand Plain, Minnesota[1]
Nitrate-nitrogen (mg/L)	4.6	2.8	0.6
Chloride (mg/L)	12.3	8.1	1.8
Sodium (mg/L)	19.4	3.8	5.6
Conductivity (µS/cm at 25°C)	851	—	442

[1]Median values.
[2]Mean values.

Seasonal Recharge

Seasonal fluctuations in recharge appear to be the major control on temporal variations in shallow ground water chemistry, a relationship that has been observed in numerous previous studies (Hallberg and Keeney 1993). As water levels rose rapidly during the spring months, concentrations of nitrate and chloride in many of the water table monitoring wells decreased (Figure 5). The “dilution effect” by infiltrating snowmelt and precipitation in spring is greatest where the water table is closest to the ground surface; temporal variability was minimal in the deep bedrock wells.

Eleven water table wells were sampled for parent atrazine in May 2002, with median and maximum concentrations of 0.2 and 0.8 µg/L. When the same wells were sampled again in October 2003, concentrations had risen to 0.4 and 1.5 µg/L, respectively. The increasing concentrations likely reflect redistribution of atrazine in the shallow ground water system over time rather than an overall increase in herbicide mass in the subsurface because atrazine was not applied at the site after the study began in 2001. These data illustrate the importance of timing on sample collection; spring recharge appears to have diluted atrazine concentrations in the May 2002 sample set. The data also indicate that atrazine, and possibly other agricultural chemicals, can be very persistent in ground water, even after a change in land use.



Well ID	$\delta^{15}N$ (per mil)	Nitrate (mg/L as N)
MW-01	8.93	4.5
MW-02	4.63	25.3
MW-04	5.55	4.5
MW-06	6.58	2.7
MW-07	4.40	19.1
MW-11	5.24	29.5
WS-3	4.16	12.0

Figure 4. Sample locations with nitrate concentrations and $\delta^{15}N$-NO_3 values. Samples (*) had $\delta^{15}N$ values between the ranges associated with commercial fertilizers and human or animal waste, although high nitrate concentrations were correlated with significantly lower $\delta^{15}N$ values.

Surface Topography

Contaminant concentrations appeared to be elevated at low points in the landscape. Shallow wells located at some of the topographically lowest points of a cropped field had the highest nitrate and atrazine concentrations. One reason for this correlation could be that runoff of applied fertilizers resulted in focused recharge of contaminants at topographic lows. This process has been documented in the sand plains of Minnesota (Delin and Landon 2002). Another possible explanation is that because the water table is closer to the ground surface at topographic lows, it is more susceptible to contaminants applied at the surface in those locations. Mehnert et al. (1995) found that the occurrence of agricultural chemicals in small-diameter wells in Illinois increased as the thickness of the unsaturated zone decreased.

Aquifer Heterogeneities

Small-scale heterogeneities may play a large role in determining the relative distribution of contaminants at the study site. For example, wells MW-02 and MW-10 (Figure 2) are screened at about the same elevation and located along the eastern boundary of the site. However, samples collected from the two wells had distinctly different chemical compositions (Table 3). Nitrate concentrations in well MW-02, which is screened in medium to coarse sand (K = 1.7 m/d), were much higher and more variable than in MW-10, which is screened in clay-rich sand (K = 0.06 m/d). It is likely that nitrogen fertilizer applied at the ground surface near both wells has a shorter transit time to ground water through the coarse sediments near MW-02. Well MW-10 also had consistently higher sulfate concentrations than any of the other wells probably due to the weathering of sulfide minerals in the surrounding clay lens that was absent at well MW-02.

Surficial Loading Patterns

Local loading patterns are a significant control on the spatial distribution of shallow ground water constituents. Fertilizers, pesticides, and road salt were the local sources of contamination at this site. Water table wells located at the edge of or beyond the cropped area had consistently lower nitrate and atrazine concentrations than those in the middle of the fertilized field. In addition, wells drilled near Highway 19 or Twin Lane Road, both of which were salted with NaCl during the winter months, had the highest sodium and chloride concentrations at the site. Both examples illustrate how local loading patterns can affect shallow ground water chemistry.

Samples collected from residential water supply wells within Savannah Valley and the nearby Drovers Woods subdivisions showed less chemical variability than the shallow water table wells. Bedrock wells had smaller concentration ranges and lower standard deviations for nitrate, chloride, sodium, and conductivity (Table 1). This is likely because the bedrock wells have long open intervals and sample ground water chemistry over that entire interval. Because the wells within each of the subdivisions are close together, they probably sample water originating from a common source area. However, rural residential wells not located in subdivisions had variable nitrate, chloride, and conductivity levels. For example, nitrate-nitrogen concentrations ranged over two orders of magnitude (0.2 to 25.6 mg/L). These homes were far enough apart that the wells likely sampled water originating from distinct source areas with varying agricultural loading rates.

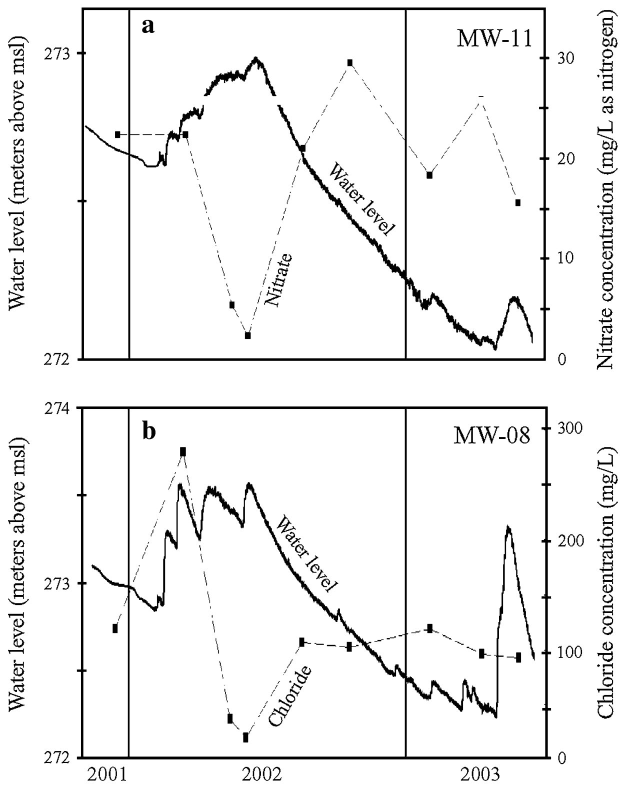


Figure 5. Seasonal variability in nitrate and chloride concentrations. (a) Nitrate concentrations in well MW-11 decreased during the spring recharge season and (b) chloride concentrations in MW-08 increased in early spring due to infiltrating road salt before dropping in late spring. Well locations are shown in Figure 2.

Well Construction

Well casing depth has been documented in many studies to play a role in the water quality sampled from water supply wells (Hallberg and Keeney 1993; Panno et al. 1996). Although nitrate-nitrogen concentrations were consistently between 2.0 and 6.5 mg/L in Savannah Valley subdivision wells and between 4.0 and 9.0 mg/L in Drovers Woods subdivision wells, two notable exceptions appear to be caused by differences in well construction.

Most bedrock wells in the area are cased 12 to 18 m below ground surface, with total well depths ranging from 30 to 50 m. One well at the Savannah Valley site was cased 11 m below land surface but <15 cm into the uppermost bedrock unit. Caliper logs suggest that this sandstone is highly fractured, and it was difficult to lower a pump down this well through the caving formation material. Elevated nitrate and chloride levels in this well suggest that preferential contaminant transport may be occurring in the upper bedrock fractures, particularly considering that the total depth of the well, 49.4 m (162 feet), is consistent with other wells having lower nitrate concentrations. A second well, located in Drovers Woods subdivision, was cased 63.4 m (208 feet) below ground surface, with a total depth of 76.8 m. This well had undetectable nitrate-nitrogen and by far the lowest chloride concentration. These data suggest that even if ground water chemistry beneath a rural subdivision has a uniform vertical profile across the site, differences in well construction can result in significant variations in water quality among private wells.

Table 3
Selected Ground Water Chemistry for Wells MW-02 and MW-10, December 2001 to May 2003

	NO_3^-	Cl^-	SO_4^{2-}	Na	K	Hardness	Alkalinity
MW-02	21.6	3.1	5.7	4.4	2.2	376	275
MW-10	1.5	5.2	50.0	8.9	3.3	311	244

Concentrations are median values in mg/L, except for hardness and alkalinity (mg/L as $CaCO_3$) and NO_3^- (mg/L as nitrogen).

Conclusions and Recommendations

For this study, we installed monitoring equipment and acquired a full year of ground water monitoring data prior to construction of new homes at a rural subdivision site in Southern Wisconsin. The most important finding is the high variability, in both space and time, of predevelopment ground water quality across this relatively small site. Thus, assumptions of negligible or uniform effects of previous agricultural land use would be inappropriate for this site and would limit the potential to assess the impacts of subdivision development on ground water quality. Concentrations of chemical parameters just below the water table exceeded the drinking water standard for nitrate in some wells and showed other evidence of land-use impacts (agricultural use and highway salting) in many wells. Concentrations in deeper bedrock wells, although lower and less variable, also showed evidence of impacts from land use. Temporal variability is primarily caused by recharge patterns because infiltrating precipitation can either dilute existing concentrations or bring in additional contaminants, depending on local conditions at the surface. Spatial variability is caused by aquifer heterogeneities, nonuniform agricultural loading patterns, and runoff of agricultural chemicals to topographically low points in the landscape. Ground water quality is much more variable near the water table than deeper in the aquifer; samples collected from bedrock wells are much more consistent over time. Well construction, particularly casing depth, apparently controls chemical variability in these wells.

These observations have several implications for the success of ground water studies attempting to identify the effects of land-use change.

1. A detailed characterization of both background ground water chemistry and chemical variability in space and time prior to land-use change can be accomplished with multiple wells and frequent sampling intervals. This is particularly important in areas where ground water chemistry is unknown or where previous land use may have resulted in ground water contamination. The variability observed in this study would not have been detected if background ground water chemistry had been determined using just a few monitoring wells within the subdivision site or inferred from wells located upgradient. However, identifying and quantifying this variability will be essential to confidently assess any future effects caused by land-use change.

2. Sampling frequency during both pre- and postconstruction time periods should account for the effects of seasonal variations and individual recharge events on ground water quality. In this study, ground water chemistry was highly variable throughout the year, and characterizing background conditions based on only one "preconstruction" sampling round would have been insufficient. A full year of background data was necessary to document seasonal variability in this study, although a multiyear data set would be even more useful to document variability between wetter and drier years.
3. Shallow monitoring wells with short screens should be used if the contaminants of interest are applied at or near the ground surface. Shallow wells are much more susceptible to local loading patterns and small-scale changes in contaminant concentrations.
4. Surface topography may be an important consideration when designing monitoring well networks. Although focused recharge in topographic lows may dilute waste water in those areas, contaminants may be transported more quickly to the water table before adequate degradation can occur in the unsaturated zone.
5. Although it may not be economical to conduct such a detailed background characterization in every study, it may be possible to focus limited resources based on expected variability. For example, at the site of this study, contaminant concentrations across the site will likely be highest during drier seasons and years when decreased precipitation will limit dilution in the aquifer. Therefore, installing wells and collecting ground water samples from the most vulnerable areas of the site during the driest times of the year would provide a "worst-case scenario" for ground water quality beneath the subdivision.

Acknowledgments

This research was funded by the University of Wisconsin Groundwater Resources Advisory Council and administered by the Wisconsin Water Resources Institute. We thank Samuel Panno and David Gosselin for their constructive comments that improved the quality of this paper.

References

American Public Health Association, American Water Works Association, and Water Environment Federation. 1998. *Standard Methods for the Examination of Water and Wastewater*, 20th ed. Washington, DC: American Public Health Association.

Anderson, H.W. 1993. Effects of agricultural and residential land use on ground-water quality, Anoka Sand Plain aquifer, east-central Minnesota. USGS Water-Resources Investigations Report 93-4074. Mounds View, Minnesota: USGS.

Aravena, R., M.L. Evans, and J.A. Cherry. 1993. Stable isotopes of oxygen and nitrogen in source identification of nitrate from septic tanks. *Ground Water* 31, no. 2: 180–186.

Bohlke, J.K., and J.M. Denver. 1995. Combined use of groundwater dating, chemical, and isotopic analyses to resolve the history and fate of nitrate contamination in two agricultural watersheds, Atlantic coastal plain, Maryland. *Water Resources Research* 31, no. 9: 2319–2339.

Canter, L.W., and R.C. Knox. 1985. *Septic Tank System Effects on Ground Water Quality.* Chelsea, Michigan: Lewis Publishers.

Carleton, G.B., and E.F. Vowinkel. 1996. Nitrate in ground water and surface water in a residential subdivision, West Windsor Township, Mercer County, New Jersey, 1993. USGS Open-File Report 96–576. West Trenton, New Jersey: USGS.

Chern, L., G. Kraft, and J. Postle. 1999. Nitrate in groundwater—A continuing issue for Wisconsin citizens. Madison, Wisconsin: The nutrient management subcommittee of the nonpoint source pollution abatement program redesign, Wisconsin Department of Natural Resources.

Dane County Regional Planning Commission (RPC). 1999. Dane County groundwater protection plan. Madison, Wisconsin: Dane County Regional Planning Commission.

Delin, G.N., and M.K. Landon. 2002. Effects of topography on the transport of agricultural chemicals to groundwater in a sand-plain setting. *Hydrogeology Journal* 10, no. 4: 443–454.

Fetter, C.W. 1994. *Applied Hydrogeology.* Upper Saddle River, New Jersey: Prentice Hall.

Fogg, G.E., D.E. Rolston, D.L. Decker, D.T. Louie, and M.E. Grismer. 1998. Spatial variation in nitrogen isotope values beneath nitrate contamination sources. *Ground Water* 36, no. 3: 418–426.

Fuhrer, G.J., R.J. Gilliom, P.A. Hamilton, J.L. Morace, L.H. Nowell, J.F. Rinella, J.D. Stoner, and D.A. Wentz. 1999. The quality of our nation's waters: Nutrients and pesticides. USGS Circular 1225. Reston, Virginia: USGS.

Goetz, W.J., C.R. Harper, C.E. Willis, and J.T. Finn. 1991. *Effects of Land Uses and Hydrogeologic Characteristics on Nitrate and Sodium in Groundwater.* Amherst, Massachusetts: Massachusetts University Water Resources Research Center.

Gold, A.J., W.R. DeRagon, W.M. Sullivan, and J.L. Lemunyon. 1990. Nitrate-nitrogen losses from rural and suburban land uses. *Journal of Soil and Water Conservation* 45, no. 2: 305–310.

Gormly, J.R., and R.F. Spalding. 1979. Sources and concentrations of nitrate-nitrogen in ground water of the Central Platte Region, Nebraska. *Ground Water* 17, no. 3: 291–301.

Hallberg, G.R., and D.R. Keeney. 1993. Nitrate. In *Regional Ground-Water Quality*, ed. W.M. Alley, 297–322. New York: Van Nostrand Reinhold.

Kelly, W.R. 1997. Heterogeneities in ground-water geochemistry in a sand aquifer beneath an irrigated field. *Journal of Hydrology* 198, no. 1–4: 154–176.

Komor, S.C., and H.W. Anderson. 1993. Nitrogen isotopes as indicators of nitrate sources in Minnesota sand-plain aquifers. *Ground Water* 31, no. 2: 260–270.

Kreitler, C.W., and L. Browning. 1983. Nitrogen isotope analysis of groundwater nitrate in carbonate aquifers: Natural sources versus human pollution. *Journal of Hydrology* 61, no. 1–3: 285–301.

Landon, M.K., G.N. Delin, S.C. Komor, and C.P. Regan. 2000. Relation of pathways and transit times of recharge water to nitrate concentrations using stable isotopes. *Ground Water* 38, no. 3: 281–395.

Mehnert, E., S.C. Schock, M.L. Barnhardt, M.E. Caughey, S.F.J. Chou, W.S. Dey, G.B. Dreher, and C. Ray. 1995. The occurrence of agricultural chemicals in Illinois' rural private wells: Results from the pilot study. *Ground Water Monitoring & Remediation* 15, no. 1: 142–149.

Midwestern Regional Climate Center. 2003. Historical climate data. http://mcc.sws.uiuc.edu/ (accessed June 2003).

Panno, S.V., I.G. Krapac, C.P. Weibel, and J.D. Bade. 1996. Groundwater contamination in karst terrain of southwestern Illinois. Illinois State Geological Survey Series EG-151. Champaign, Illinois: Illinois State Geological Society.

Saffigna, P.G., and D.R. Keeney. 1977. Nitrate and chloride in ground water under irrigated agriculture in central Wisconsin. *Ground Water* 15, no. 2: 170–177.

Shanley, J.B., E. Pendall, C. Kendall, L.R. Stevens, R.L. Mihel, P.J. Phillips, R.M. Forester, D.L. Naftz, B. Liu, L. Stern, B.B. Wolfe, C.P. Chamberlain, S.W. Leavitt, T.H.E. Heaton, B. Mayer, L.D. Cecil, W.B. Lyons, B.G. Katz, J.L. Betancourt, D.M. McKnight, J.D. Blum, T.W.D. Edwards, H.R. House, E. Ito, R.O. Aravena, and J.F. Whelan.

1998. Isotopes as indicators of environmental change. In *Isotope Tracers in Catchment Hydrology*, ed. C. Kendall and J.J. McDonnell, 761–816. Amsterdam: Elsevier Science B.V.

Shaw, B., P. Arntsen, and W. VanRyswyk. 1993. Subdivision impacts on groundwater quality. Madison, Wisconsin: Wisconsin Department of Natural Resources.

Thomas, M.A. 2000. The effect of residential development on ground-water quality near Detroit, Michigan. *Journal of the American Water Resources Association* 36, no. 5: 1023–1038.

Tinker, J.R. 1991. An analysis of nitrate-nitrogen in ground water beneath unsewered subdivisions. *Ground Water Monitoring Review* 11, no. 1: 141–150.

Trojan, M.D., J.S. Maloney, J.M. Stockinger, E.P. Eid, and M.J. Lahtinen. 2003. Effects of land use on ground water quality in the Anoka Sand Plain Aquifer of Minnesota. *Ground Water* 41, no. 4: 482–492.

U.S. Census Bureau. 2004. American Housing Survey for the United States: 2003. http://www.census.gov/prod/2004pubs/H150–03.pdf (accessed September 2004).