Wisconsin Geological and Natural History Survey
DIVISION OF EXTENSION
UNIVERSITY OF WISCONSIN–MADISON

Assessing private well contamination in Grant, Iowa, and Lafayette counties: The southwest Wisconsin groundwater and geology study

Final report to Grant, Iowa, and Lafayette counties (May 2022)

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Contents

How to read this report

The study described in this report involved 816 private wells, included five study objectives, and generated thousands of pages of data. It is one of the largest and most comprehensive private well studies in the nation. As such, it provides value at two levels: the local knowledge for residents of Grant, Iowa, and Lafayette Counties and the broader contribution to groundwater science.

The report is organized into discrete sections that can be read independently. Following the summary and background, there is one section for each of the five study objectives, with each section organized as follows: a) objective, b) approach, c) key findings, d) context and interpretation, e) strengths and limitations, and f) conclusions.

The report can be read at several levels. Reading the summary alone will provide the important highlights. More detailed highlights are given in the "key findings" sub-section under each objective, and a discussion of the results is included in each "context and interpretation" sub-section. The reader may wish to focus on one or two objectives, in which case it is not necessary to read the other objectives because each can generally stand alone. For greater detail, the appendices can be read for technical information and additional data. Finally, the study will also be reported in a peer-reviewed scientific journal publication with an emphasis on technical information and the broader scientific context.

Summary

Rural residents of Grant, Iowa, and Lafayette Counties in Wisconsin rely on private wells for their water. Contaminants like nitrate and bacteria from septic systems, fertilizer, and manure can contaminate the groundwater that residents use. Groundwater is vulnerable to contamination where the soil layer is thin and the bedrock is fractured, which is the case for much of the study region. This study includes five objectives that were designed to assess and understand private well water contamination in the three counties.

Objective 1. Extent of private well contamination

The extent of bacteria and nitrate private well contamination was determined by testing randomly selected wells in two water sampling events. A total of 840 water samples were tested for nitrate, total coliform bacteria, and E. coli, which are standard tests of well water quality. Overall, 126 (42%) of 301 wells sampled in November 2018 and 145 (27%) of 539 wells sampled in April 2019 were positive for total coliform bacteria and/or had nitrate greater than the Wisconsin and U.S. Environmental Protection Agency health standard (10 mg nitrate-nitrogen per liter). The percentage of study wells with total coliforms or high nitrate was generally greater than statewide percentages for private wells.

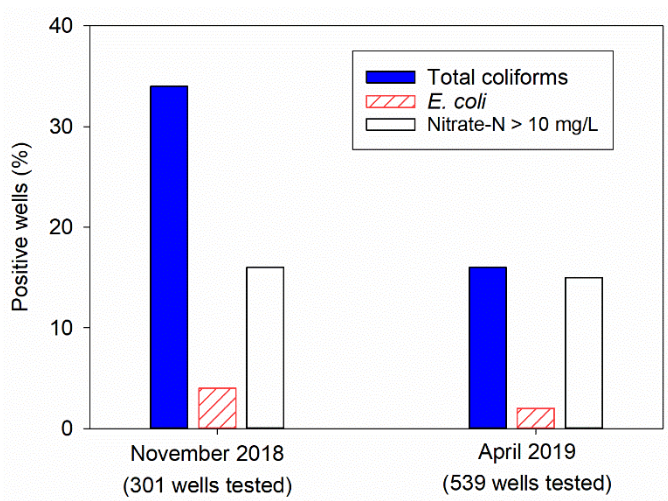

Figure 1. Percentage of wells positive for total coliforms and E. coli and with high nitrate. Wells were randomly selected and tested in November 2018 or April 2019.

Objective 2. Human wastewater and livestock manure contamination

Tests that distinguish between human wastewater, bovine (cattle) manure, and porcine (pig) manure were used to identify fecal sources of contamination. For these tests, 138 wells were randomly selected from those positive for total coliforms or with high nitrate (Figure 2). Human wastewater was detected in 64 wells, cattle manure was detected in 33 wells, and pig manure was detected in 13 wells, indicating that both human wastewater and livestock manure contribute to private well contamination. The tests identify the three specific fecal sources but not other types of contamination, like chemical fertilizers or manure from other animals. These tests cannot determine the source of contamination for nitrate, total coliforms, or *E. coli*, which can originate from many places.

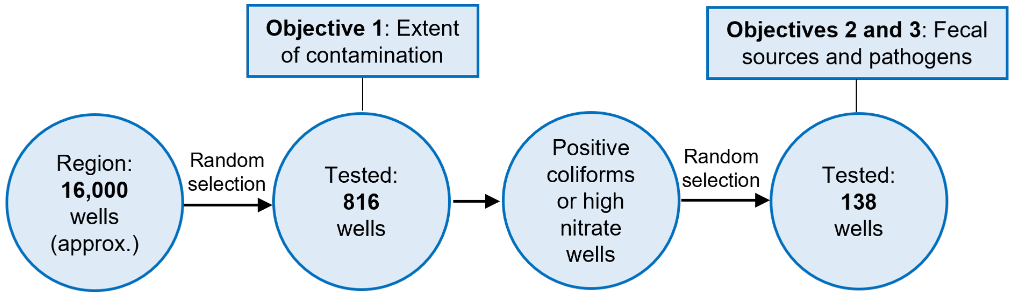

Figure 2. Wells for Objective 1 were randomly selected from all wells in the region. Wells for Objectives 2 and 3 were randomly selected from wells tested in Objective 1 that were positive for total coliforms and/or had high nitrate. The same 138 well water samples were tested for Objectives 2 and 3.

Objective 3. Pathogens in private wells

Residents may become ill from drinking water that contains pathogens, like viruses and bacteria. The 138 wells tested for Objective 2 were also tested for pathogens. These wells were randomly selected from those positive for total coliforms or with high nitrate (Figure 2). Pathogens were detected in 66 of the 138 wells (48%). Many of the pathogens can be passed between humans and animals, so their source was often unknown.

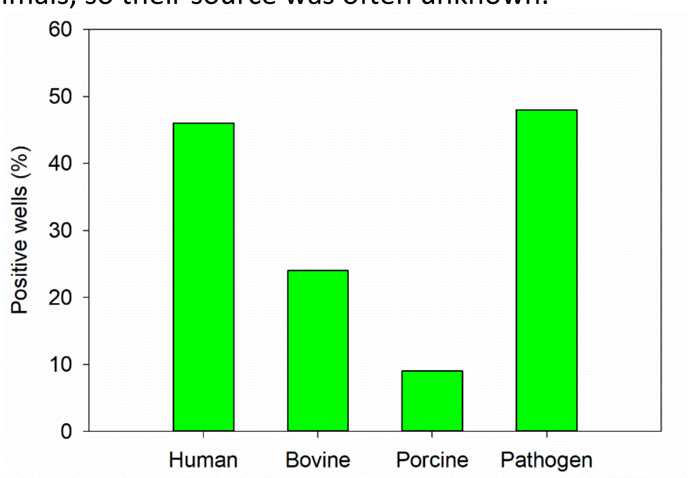

Figure 3. Percentage of 138 wells positive for human wastewater, bovine manure, porcine manure, and pathogens. Wells were randomly selected from those positive for total coliforms and/or with high nitrate and were sampled in one of four seasonal events.

Objective 4. Factors related to contamination: well characteristics, well siting, geology, rainfall and groundwater levels

Well characteristics, well siting, geology, rainfall, and groundwater levels were examined for relationships to the contaminants measured in Objectives 1 and 2. These factors affect the tendency for contaminants to reach groundwater or enter wells. Nitrate contamination was generally greater where the geology allows rapid flow of water and contaminants. Microbial

Considering well characteristics & geology in southwest Wisconsin, private well contamination tends to increase if…	
Nitrate:	
Age of well	*is older*
Casing depth	*is shallower*
Casing length into bedrock	*is shorter*
Well depth	*is shallower*
Geology	*is fractured or sand/gravel*
Total coliforms:	
Age of well	*is older*
Casing depth	*is shallower*
Casing length into bedrock	*is shorter*
Casing length into groundwater	*is shorter*
Open interval length	*is longer*
Open interval	*crosses aquifers*
Bedrock depth	*is shallower*
Human wastewater:	
Age of well	*is older*
Well depth	*is shallower*
Bedrock depth	*is shallower*
Livestock manure:	
Open interval length	*is shorter*
Geology	*is sandstone*

Figure 4. Table with a summary of well characteristics and geologic factors related to private well contamination.

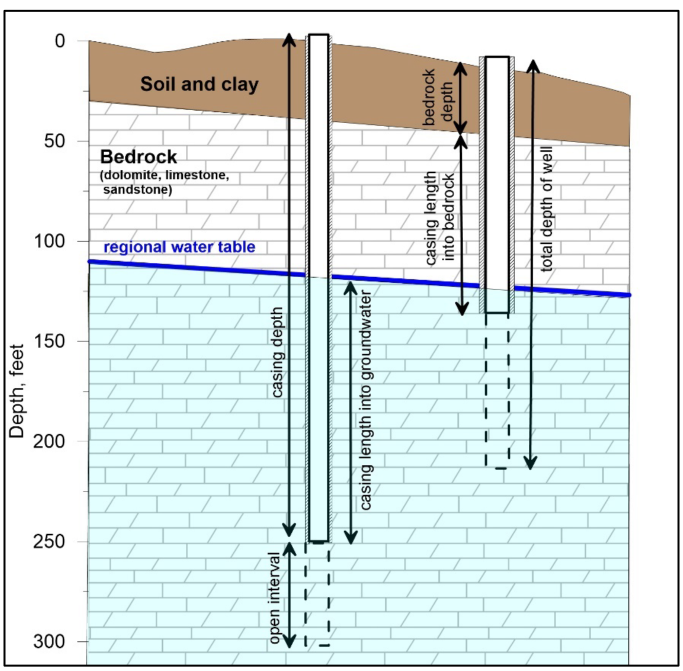

Figure 5. Cross-section illustration of well characteristics that were examined for relationships with contamination.

contamination was generally greater following periods of rainfall and where bedrock is closer to the surface. Both nitrate and microbial contamination were generally greater for older, shallower wells. The factors reflect probabilities, not absolutes. For example, high nitrate is more likely for shallow wells, but this does not mean that all wells that are shallow will have high nitrate.

Objective 5. Factors related to contamination: septic systems, farms, and cultivated land

Septic systems, farms, and cultivated land were examined for their relationships with the contaminants measured in Objectives 1 and 2. Human wastewater contamination was greater for wells closer to septic systems and for wells with more septic systems nearby. Septic systems were not associated with nitrate and total coliforms. Nitrate and total coliforms contamination were greater for wells closer to farms or cultivated land (fields used for crops like corn). Also, nitrate contamination increased when the area of cultivated land nearby was larger. Like Objective 4, these factors reflect probabilities, not absolutes.

Considering land use in southwest Wisconsin, private well contamination tends to increase if…	
Nitrate:	
Cultivated land area nearby ……………………........	*is larger*
Cultivated land……………………………………...........	*is closer*
Livestock farms………………………………..................	*are closer*
Total coliforms:	
Livestock farms………………………………..................	*are closer*
Human wastewater:	
Septic system count nearby…………………..........	*is greater*
Septic systems…………………....................................	*are closer*
Livestock manure:	
Cultivated land area nearby…………………..............	*is larger*
Cultivated land……………………………….................	*is closer*
Livestock farms………………………………..................	*are closer*

Figure 6. Table with summary of land use factors related to private well contamination.

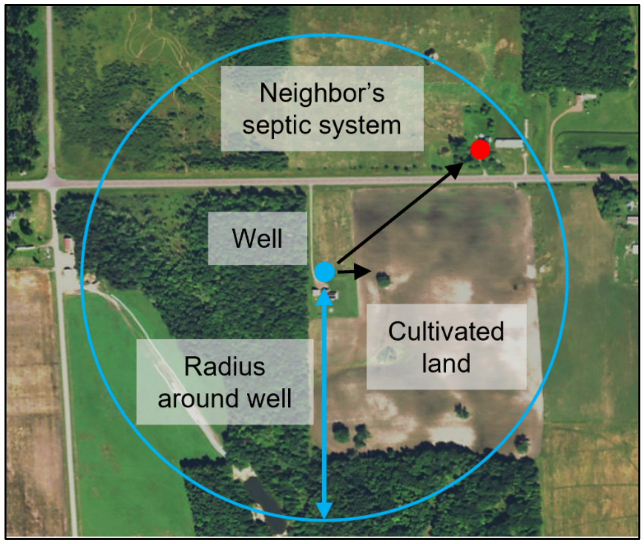

Figure 7. Illustration of land use surrounding a well. Land use factors included the distance to cultivated land, the area of cultivated land within a set radius around the well, the distance to the nearest septic system, and the number of septic systems within a set radius around the well.

Applicability to other counties and regions

The study describes private well contamination for southwest Wisconsin. Because geology, land use, and well construction can affect contamination, they must be considered when applying these findings in other regions. For example, findings may be more relevant to regions with carbonate rock geology (which is common in the study area) than to regions with sand aquifers (which is less common in the study area). However, regions with similar geology may have different sources of contamination because land use differs. For example, urban or forested areas may have different contamination sources than the rural, agricultural region where this study took place.

Broadly speaking, the study shows that nitrate, fecal waste, and pathogens can enter groundwater. It also shows that private well contamination is related to the sources of these contaminants and how they move to and through groundwater. These broader observations reflect existing knowledge that applies beyond southwest Wisconsin.

Study outcomes

The study produced two general outcomes related to groundwater quality in southwest Wisconsin. First, the study describes the extent of private well contamination based on standard tests of water quality (Objective 1), and it further indicates the potential for pathogens to contaminate private wells (Objective 3). Second, the study describes the sources of contamination and shows that contamination was related to multiple factors (Objectives 2, 4, and 5). By identifying multiple sources and factors related to private well contamination, the study may be used when considering potential priorities for groundwater quality. Importantly, the study goes beyond a description of contamination, and it may also be used to inform efforts or actions that address contamination. Together, these two outcomes provide a unique contribution to groundwater science and a detailed characterization of private well drinking water quality for the residents of southwest Wisconsin.

Background

Residents in rural areas of Grant, Iowa, and Lafayette Counties rely on private wells for their drinking water. There are approximately 16,000 construction records for private wells in the three-county region (Wisconsin Department of Natural Resources (WDNR) Well Construction Information System), and there are additional wells for which construction records are unavailable. Water quality for private wells is not regularly monitored by federal, state, or local government, so homeowners are responsible for the maintenance and testing of their private well.

Well water quality is commonly assessed by testing for indicator bacteria (total coliforms and *E. coli*) and nitrate (Appendix 1). Total coliforms are a group of bacteria that includes *E. coli*, and their presence in a well indicates that microbial contaminants near the land surface can reach well water. While total coliforms are generally not harmful, Wisconsin DNR recommends corrective actions when they are detected in private wells (WDNR 2017; WDNR 2021). Nitrate-nitrogen (NO_3^--N) concentrations greater than 10 mg/L exceed Wisconsin's groundwater quality standard, which is consistent with the maximum contaminant level given by the U.S. Environmental Protection Agency for public water systems (USEPA 2022; WDNR 2010, 2021).

Bacteria in groundwater can originate from fecal sources, like manure and wastewater, and from non-fecal sources. Nitrate can originate from fecal sources, chemical fertilizers, and natural sources. Bacteria and nitrate are carried to groundwater by rain and melting snow. Well defects can contribute to contamination, but properly constructed wells can also be subject to contamination when groundwater is contaminated from sources on the landscape.

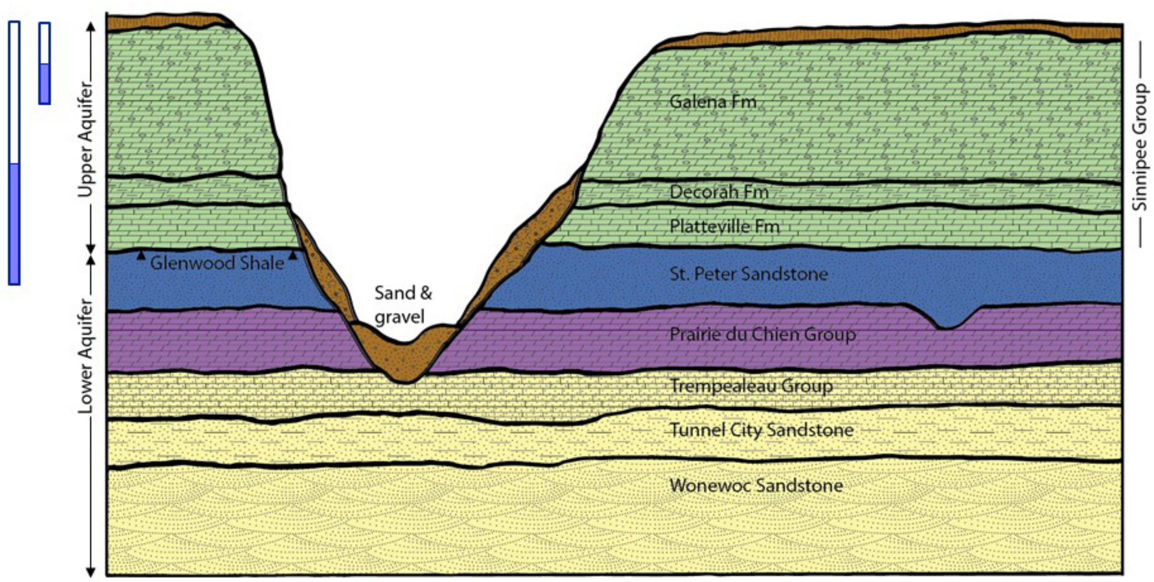

Figure 8. Cross section of bedrock layers. Upper and lower aquifers are indicated on the left; they are separated by the Glenwood Shale (the shale is too thin to show as a separate unit). Water levels in deep wells finished in the lower aquifer can stand far below water levels in shallower wells finished in the upper aquifer, as illustrated at the left. The Sinnipee Group is indicated on the right; it is the topmost bedrock in much of the region but is absent in some areas (see Figure 9 and Appendix 2).

In addition to contaminant sources, geology influences the vulnerability of groundwater to contaminants. The regional hydrogeology is summarized in Appendix 2. The bedrock in Grant, Iowa, and Lafayette Counties includes multiple layers that can be grouped into two bedrock aquifers, lower and upper, separated by an aquitard called the Glenwood Shale. Sand and gravel forms a third aquifer in valley bottoms (Figure 8; Carson 2012). The lower aquifer consists of sandstone and dolomite. The upper aquifer is composed of dolomite and limestone of the Sinnipee Group. The Sinnipee Group is the uppermost bedrock in most of the study area (Figure 9), and these carbonate rocks have fractures and voids that allow water and contaminants to move quickly. Given the bedrock's limited ability to filter contaminants, the soil overlying bedrock is essential for removing contaminants prior to reaching the groundwater. There is less than 50 feet of soil and sediment in much of the study area (Wisconsin Geological and Natural History Survey 2009), and areas with shallow soils and fractured bedrock are often considered vulnerable to contamination.

Objectives

The objectives of this research were designed to assess the extent, sources, and factors of private well water contamination in Grant, Iowa, and Lafayette Counties. The original research proposal included three objectives (numbers 1, 2, and 4 in the list below). Two objectives (numbers 3 and 5) were added after the project was initiated to provide additional information, and the scope of one of the original objectives was expanded (Objective 4). Results for the following 5 objectives are presented in this report:

1) Evaluate private well contamination in three counties (Grant, Iowa, and Lafayette) using indicator bacteria (total coliforms and *E. coli*) and nitrate based on randomized synoptic ("snapshot") sampling events.
2) Identify fecal sources of contamination in a subset of wells that were positive for total coliforms and/or had high nitrate. Sample once per season and use microbial tests that distinguish between human, bovine, and porcine fecal sources.
3) Analyze private well samples collected for Objective 2 for genes specific to certain pathogens.
4) Assess well construction and geologic characteristics (e.g., well age, bedrock depth) that are related to well contamination.
5) Identify land use factors and potential contamination sources (e.g., number of nearby septic systems, distance to an agricultural field) related to well contamination.

Objective 1

Objective

Evaluate private well contamination in three counties (Grant, Iowa, and Lafayette) using indicator bacteria (total coliforms and *E. coli*) and nitrate based on randomized synoptic ("snapshot") sampling events.

Approach: Well selection and sample collection

To produce a representative estimate of contamination in the study area, private wells were sampled in two synoptic ("snapshot") events: November 9 – 10, 2018 and April 11 – 12, 2019. Wells were randomly selected irrespective of county. Invitations were sent to 1,250 well owners in November and 2,083 in April, and 25% of invited well owners participated. Well owners collected samples using kits and instructions provided by the laboratory. Project staff delivered samples the day they were collected to the Water and Environmental Analysis Laboratory at the University of Wisconsin-Stevens Point for analysis of total coliforms, *E. coli*, and nitrate, which are standard tests of water quality. Appendix 3 describes sample collection and analysis. Testing was free to participants, and well owners received their individual test results. A total of 840 samples from 816 randomly selected private wells were tested, including 24 wells sampled in both events.

Groundwater contamination changes over time, and the study approach was designed to account for this fact in two ways. First, the synoptic sampling design minimized short-term variation in source and transport conditions, like rainfall, by sampling wells over a short period. Results for each two-day synoptic sampling event therefore represent contamination in the study area under the conditions around the time that samples were collected. Second, the study was designed to capture longer-term variation in source and transport conditions by including two events that were five months apart.

Key findings

- 126 (42%) of 301 private wells sampled in November 2018 and 145 (27%) of 539 private wells sampled in April 2019 were positive for total coliform bacteria and/or had nitrate greater than the drinking water standard of 10 mg NO_3^--N/L (Table 1). These percentages are greater than or similar to statewide percentages for private wells.
- Contaminated private wells were distributed across the study area (Figure 9).
- The percentage of wells with high nitrate was similar between the two sampling events, while the percentage of wells positive for total coliforms differed (Table 1). Variation in private well contamination from one point in time to another is expected because contamination sources and transport conditions, like rainfall, change.
- The mean concentration for samples with detectable nitrate was 6 mg NO_3^--N/L (maximum of 67 mg NO_3^--N/L), and the concentrations for total coliforms and *E. coli* tended to be low, on the order of ones to tens Most Probable Number per 100 mL (Table 2).

Table 1. Percentage of wells positive for indicator bacteria (total coliforms and *E. coli*) or with NO_3^--N greater than 10 mg/L in two synoptic sampling events and comparison to statewide data. Results for each county are presented in Appendix 5.

Synoptic event or statewide data	No. wells tested	Total coliforms	*E. coli*	NO_3^--N > 10 mg/L	Total coliforms and/or NO_3^--N > 10 mg/L
November 2018	301	34%	4%	16%	42%
April 2019	539	16%	2%	15%	27%
Statewide 1997[a]	534	23%	3%	7%	-
Statewide 2013[b]	3838	18%	-	10%	-
Statewide 2017[c]	401	-	-	8%	-

Note: "-" indicates data were not reported. The symbol ">" indicates "greater than."
[a]U.S. General Accounting Office 1997
[b]Knobeloch et al. 2013
[c]Wisconsin Department of Agriculture, Trade, and Consumer Protection (WDATCP) 2017

Table 2. Concentrations of samples positive for total coliforms, *E. coli*, and nitrate.

Synoptic event	Measurement	No. positive[a]	Median	Mean[b]	Minimum	Maximum
Nov. 2018 (301 wells)	Total coliform (MPN/100 mL)	102	6	65	1	>2420
	E. coli (MPN/100 mL)	13	2	13	1	135
	Nitrate (mg NO_3^--N/L)	223	4	6	0.1	36
Apr. 2019 (539 wells)	Total coliform (MPN/100 mL)	85	4	32	1	>2420
	E. coli (MPN/100 mL)	9	2	93	1	770
	Nitrate (mg NO_3^--N/L)	429	4.3	6	0.1	67

Note: MPN, Most Probable Number (units used for measurement of total coliforms and *E. coli*). The groundwater quality standard is 0 MPN/100 mL (WDNR 2017, 2021).
[a]For nitrate, includes nitrate detected at any concentration. The groundwater quality standard is 10 mg/L (WDNR 2010, 2021).
[b]Mean excludes samples with total coliform greater than the upper detection limit (2 for each event).

Context and interpretation

Groundwater contamination can change. The synoptic sampling events provide two "snapshots" of private well contamination. The percentage of wells that were contaminated by total coliforms differed between the two events, consistent with the transient nature of groundwater contamination by microbes (Borchardt et al. 2021; Bradbury et al. 2013; Stokdyk et al. 2020). The difference in total coliforms contamination from November to April may reflect a change in the sources of these bacteria, or it may reflect differences in rain or snowmelt that carried the bacteria to groundwater. The fact that nitrate contamination was similar for the two events may indicate that the contaminant sources differed for nitrate and total coliforms, or it may reflect differences in the contaminants themselves. For example, total coliform bacteria are affected by temperature and moisture and can die in the environment, so they are expected to be less persistent than nitrate, which is a chemical that can persist for decades (Nolan 2001). Microbes (like total coliforms) and chemicals (like nitrate) behave differently when moving to and through groundwater (Hunt and Johnson 2017).

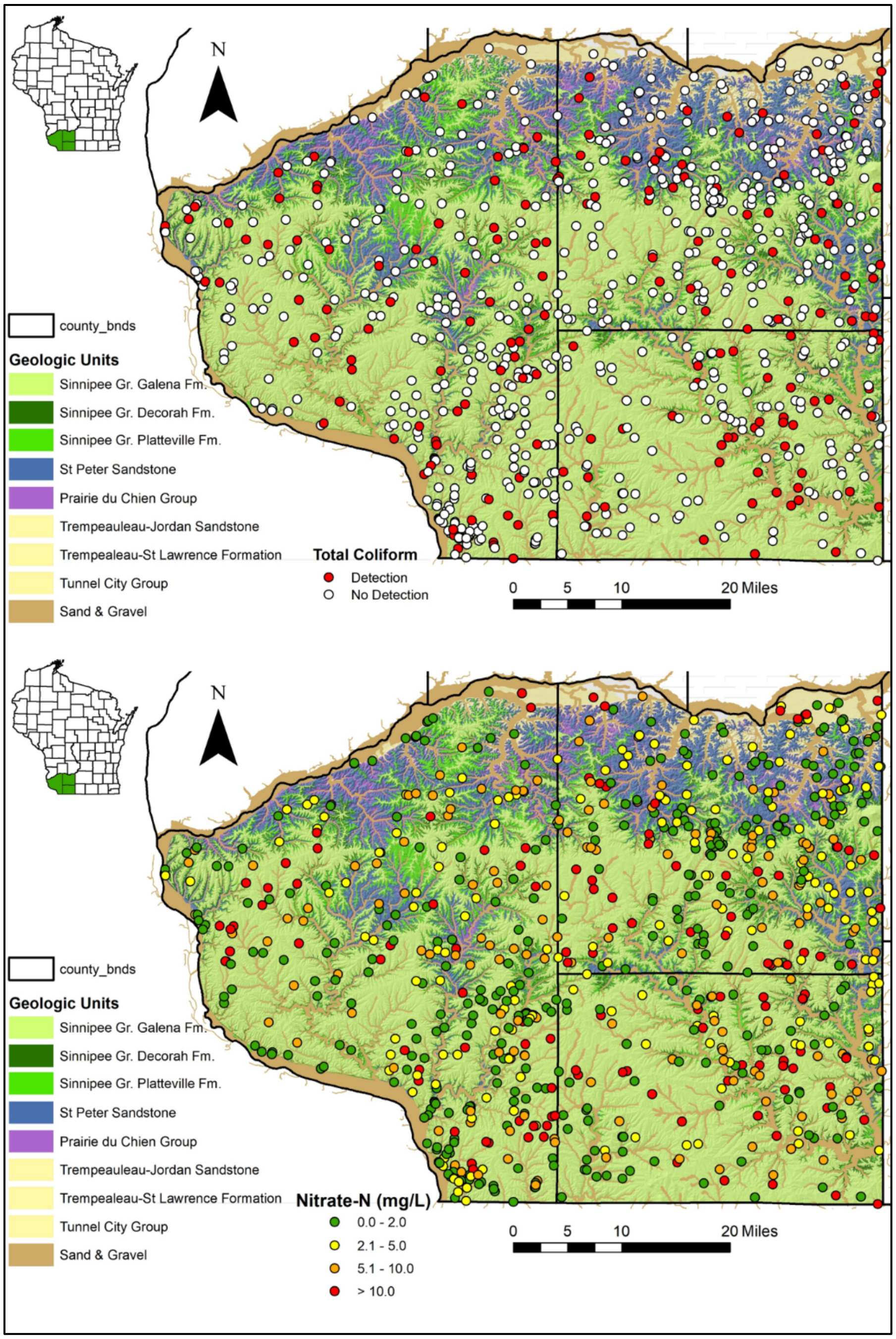

Figure 9. Total coliforms (top panel) and nitrate (bottom panel) results for the two synoptic sampling events.

<u>Comparison to private well data in Wisconsin</u>. Data prior to the current study (from UW-Stevens Point Center for Watershed Science and Education Well Water Quality Viewer in 2018) show that across the three counties 13% of 4,283 samples exceeded 10 mg NO_3^--N/L, while 29% and 3% of 1,747 samples were positive for total coliforms and *E. coli*, respectively. These percentages are similar to results from the current study, but the previous data reflect samples

collected over time (rather than synoptically) and on a voluntary basis (rather than selected randomly).

The percentage of contaminated private wells in the study area generally equaled or exceeded statewide percentages based on tests for total coliforms, *E. coli*, and nitrate (Table 1). Specifically, the percentage of wells with high nitrate in both synoptic events (15 - 16%) was greater than statewide percentages of 7 to 10% (WDATCP 2017; Knobeloch et al. 2013; U.S. General Accounting Office 1997). The percentage of study wells positive for total coliforms in November (34%) was greater than statewide percentages of 23% and 18%, but the percentage of positive study wells in April (16%) was not (Knobeloch et al. 2013; U.S. General Accounting Office 1997). The percentage of study wells positive for *E. coli* was not different from statewide percentages. Three reports were used for comparison to the current study, so the statewide data include samples collected in various seasons and years.

The percentage of contaminated private wells in the study also generally equaled or exceeded percentages from a similar study in Kewaunee County, Wisconsin, which is a rural area underlain by fractured dolomite. A recent groundwater study there used the same randomized synoptic sampling design and found that 34% of 323 private wells in one sampling event and 31% of 401 private wells in a second event were positive for total coliforms or had high nitrate (Borchardt et al. 2021). In that study, 27% and 22% of wells were positive for total coliforms in the two synoptic events, and 12% and 11% of wells had high nitrate (Borchardt et al. 2021).

Strengths and limitations

Testing many wells using a randomized, synoptic sampling design produced data that represent the study region, including variation in land use, geology, and well characteristics, while limiting the effects of weather or other factors that change over time. Fall and spring synoptic sampling events were included to assess contamination at different points in time, but the study was not designed to formally assess seasonal differences or temporal trends.

Conclusions

Results of Objective 1 are based on a randomized selection of wells and describe the extent of private well contamination in the study area in terms of standard water quality tests. The percentage of wells in the region that were positive for indicator bacteria or had high nitrate equaled or exceeded statewide percentages for private wells and may provide a benchmark for future monitoring. Nitrate contamination was similar for the two events while total coliforms differed, consistent with the fact that groundwater contamination can vary with factors that change over time.

Objective 2

Objective

Identify fecal sources of contamination in a subset of wells that were positive for total coliforms and/or had high nitrate. Sample once per season and use microbial tests that distinguish between human, bovine, and porcine fecal sources.

Approach: Well selection, sampling, and analysis

Wells for Objective 2 were randomly selected from wells tested in Objective 1 that were positive for total coliforms or had nitrate greater than 10 mg NO_3^--N/L. This subset of wells was sampled again to identify fecal sources of contamination. We selected from wells that were previously contaminated to increase the chances of identifying fecal sources in the groundwater samples, but the tests were not intended to determine the fecal sources of total coliforms and nitrate (see "Strengths and limitations" below). We sampled 34 or 35 different wells in each of four seasonal events (April 9 – 13, August 5 – 8, and November 4 – 7 of 2019 and March 3 – 6 of 2020) for a total of 138 wells.

Samples were collected by laboratory staff from a tap prior to any treatment systems. The tap was sterilized with flame, and new equipment was used for each sample. One liter of water was collected in a sterile bottle, and then a large volume of water (approximately 200 gallons) was run through a hemodialysis filter that captures microbes as the water passes through it (Figure 10). Both sample types were tested for the same microbes. We used these two sample collection methods, both of which are established and used by scientists worldwide, because each has strengths and weaknesses, and combining their results provides a comprehensive assessment of contamination.

Fecal sources were identified by microbial source tracking (MST), in which samples are tested for microbes that are found in the fecal material of certain animals. Well water samples were analyzed for 17 genetic tests for microbes that are specific to human, bovine/ruminant, or porcine fecal material; these are referred to as human wastewater markers and livestock manure markers (collectively "fecal markers"). The most frequently detected fecal markers do not cause illness, though pathogens (microbes that cause illness) were also detected (see Objective 3). Negative controls were analyzed alongside samples to ensure that laboratory contamination was absent. Laboratory procedures are described in Appendix 3 and Borchardt et al. (2021).

Key findings

- Overall, 78 of 138 wells (56%) were positive for microbes that indicate the presence of a specific fecal source (Table 3), including 26 wells positive for microbes from multiple fecal sources. Results for each county are reported in Appendix 5.
- Among the 138 wells sampled, human wastewater was detected in more wells (46%) than bovine/ruminant manure (24%) and porcine manure (9%).
- Additional wells were positive for fecesborne microbes that are not specific to a fecal source (see Objective 3).

Table 3. Microbial source tracking (MST) results identifying fecal sources in 138 private wells sampled in four events (34 or 35 wells per event).

		Number of positive wells				
Fecal source	Fecal marker	April (n = 35)	August (n = 34)	November (n = 34)	March (n = 35)	Total (n = 138)
Human wastewater	*Bacteroidales*-like HumM2	6	2	2	2	12
	Cryptosporidium hominis	1	3	4	0	8
	Human adenovirus groups A-F	2	0	0	0	2
	Human *Bacteroides* (HF183/R287)	29	12	9	6	56
	Human enterovirus	1	0	0	0	1
	Human polyomavirus	0	0	0	0	0
	Norovirus genogroup I	0	0	0	0	0
	Any human wastewater marker[a]	30	14	12	8	64
Bovine/ruminant manure	*Bacteroidales*-like Cow M2	0	0	0	0	0
	Bacteroidales-like Cow M3	0	0	0	0	0
	Bovine adenovirus	0	0	0	1	1
	Bovine enterovirus	0	1	0	0	1
	Bovine polyomavirus	1	0	0	0	1
	Ruminant *Bacteroides*	16	7	7	2	32
	Any bovine or ruminant manure marker[a]	17	7	7	2	33
Porcine manure	Pig-1-*Bacteroidales*	3	1	1	2	7
	Pig-2-*Bacteroidales*	3	1	2	2	8
	Porcine epidemic diarrhea virus	0	0	0	0	0
	Porcine adenovirus	0	0	0	0	0
	Any porcine manure marker[a]	5	1	3	4	13

[a]The number of positive wells for any human wastewater marker and any livestock (bovine and porcine) manure marker does not equal the sum of individual markers because some wells were positive for multiple markers.

Note: In addition to the microbial source tracking markers, the plant pathogen "pepper mild mottle virus" was detected in 10 wells. It is common in human wastewater and often used as a marker of human fecal contamination, but it may originate in other sources and was therefore not included in the count of wells positive for human wastewater. Most (7 of 10) wells positive were also positive for a human wastewater marker.

Context and interpretation

Fecal loading to the landscape. Septic systems and agricultural manure are common sources of human, bovine, and porcine fecal material. There are approximately 15,930 septic systems in the three-county region according to county records, which release an estimated total of 687 million gallons of effluent per year. Even properly functioning septic systems release nitrate and microorganisms (Lusk et al. 2017; Murphy et al. 2020). Land application of septage and sludge is a lesser source of human fecal material in the study area. Wisconsin DNR records for 2018 indicate that 82 fields (totaling 753 acres) received a total of 6.9 million gallons of septage or municipal sludge in one year, which is 1% of the effluent volume released from septic systems annually. The 368,128 cattle in the study area produce an estimated 2.4 billion gallons of manure per year, and the 77,600 pigs produce an estimated 39 million gallons of manure per year. Fecal volume computations are provided in Appendix 6.

While the estimated volume of cattle manure produced annually in the study area is three times greater than the estimated volume of septic system effluent, more wells were positive for human wastewater markers than bovine. The timing, location, and form of wastewater and manure on the landscape may contribute to the difference in the percentage of wells contaminated by each. For example, septic system effluent is released continuously, while manure that is stored and land-applied to fields is present intermittently. In addition, farmland comprises 80% of the study area, so manure is potentially distributed over a larger area than septic systems, which would result in a lower fecal source density. The prevalence of pasture (15% of farmland in the study area) and cattle grazing may likewise be a factor (NASS 2019). Finally, wastewater from septic systems is released underground, sheltering it from desiccation and microbe-killing sunlight while also giving it a shorter travel distance to the groundwater table than manure applied to the land surface. Overall, both human and livestock fecal sources were detected in wells.

Comparison to other private well data. Microbial source tracking analyses that identify the fecal sources of contamination are not common for private wells, and statewide data are not available for comparison. Among studies in the United States and Canada that tested private wells for fecal markers, the percentage of samples positive for human, bovine, or porcine fecal markers varied considerably (from 0 to 61%), which reflects variation in land use, geology, groundwater dynamics, well characteristics, well selection, and the tests used (Allevi et al. 2013, Felleiter et al. 2020, Krolik et al. 2014, Murphy et al. 2020, Zhang et al. 2014). Like the current study, human wastewater markers were detected in more private well samples than bovine when both were analyzed (Felleiter et al. 2020, Krolik et al. 2014, Zhang et al. 2014). Results for the three-county study area in southwest Wisconsin fall within the broad range reported in other studies, though the number of studies for comparison is limited.

The study in Kewaunee County, Wisconsin also found that both human and livestock fecal sources contributed to contamination (Borchardt et al. 2021). Specifically, 33 and 44 of 131 wells were positive for human wastewater and bovine manure markers, respectively (porcine manure was not included). The dominant fecal sources (manure and septic systems) and fractured bedrock in Kewaunee County are generally similar to that of southwest Wisconsin but differ in ways that may affect groundwater contamination.

First, the quantity, form, distribution, and timing of fecal sources on the landscape may differ in the two study areas. For example, the density of septic systems and cattle is greater in Kewaunee County (2 septic systems and 49 cattle per 100 acres) than the three-county study area in southwest Wisconsin (1 septic system and 23 cattle per 100 acres). The percentage of cattle on large farms (farms with >500 cattle) is greater in Kewaunee County (76% of cattle) than in southwest Wisconsin (35%), and the percentage of farmland in pasture is greater in southwest Wisconsin (15%) than in Kewaunee County (2%; NASS 2019, Bay Lake Regional Planning Commission 2016). Second, topography and the specific geology differ, which can affect the transport of contaminants to groundwater (Hynds et al. 2014; Murphy et al. 2017). Likewise, groundwater levels and precipitation differed, which also affect contaminant transport (Hunt and Johnson 2017; Murphy et al. 2017). Overall, both studies identified contamination of private wells by human and agricultural sources in a fractured aquifer setting.

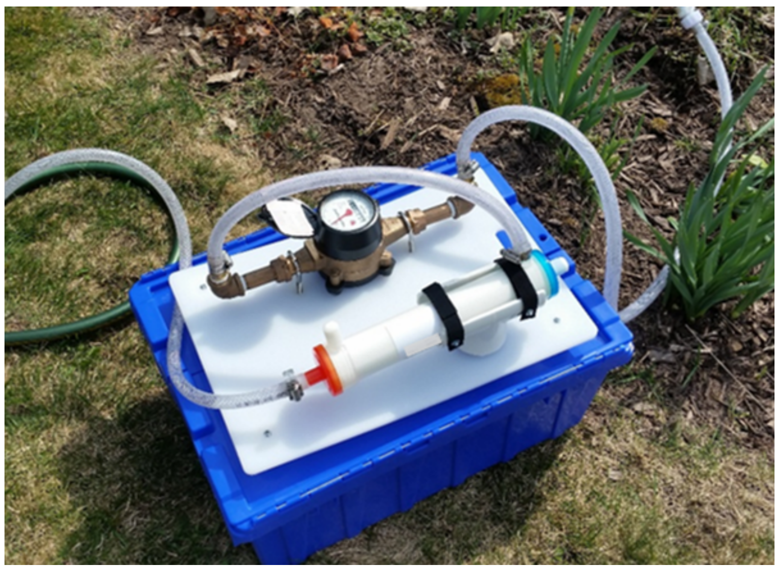

Figure 10. Microbes in wells were captured by running 200 gallons of water through hemodialysis filters.

Strengths and limitations

The number of wells positive for human wastewater, bovine/ruminant manure, and porcine manure is expected to vary over time as fecal sources and weather change, and we included seasonal sampling events to capture such variation. However, a single sampling event per season is insufficient to characterize contamination by season or generalize results to future years. For example, microbial contamination for the April sampling event is not necessarily indicative of other springs, and the number of wells contaminated in spring may not always be greater than the number contaminated in other seasons.

Because they detect genetic signatures, the tests used for Objective 2 are highly specific to the fecal source and have been validated and used in the scientific literature (Appendix 3). Multiple fecal markers were used for each fecal source, which increases the chances of detecting fecal material when it is present. While the genetic tests do not indicate whether the microbes were alive or dead, the presence of host-specific microbes identifies the fecal source regardless.

Fecal markers for human, bovine/ruminant, and porcine fecal material were included, but other fecal sources (e.g., poultry, wildlife) can also contaminate wells. One of the commonly detected manure markers, ruminant *Bacteroides*, is shed not only by cattle but also by other ruminants, including deer. There are an estimated 88,600 deer in the study area (WDNR 2018). However, the estimated total mass of fecal material produced annually by cattle in the study area (8.9 billion kg per year) is 1,000 times greater than that of deer (8.4 million kg per year; see Appendix 6). Also, previous research using this ruminant *Bacteroides* test for private wells showed that the genetic signatures all matched bacteria from cattle manure (Borchardt et al. 2021).

Wells for Objective 2 were selected from those that previously tested positive for total coliforms or had high nitrate, but the tests for fecal source do not identify the sources of nitrate and total coliforms in these wells because 1) total coliforms can originate from non-fecal sources, and the MST tests only identify fecal sources, 2) nitrate can originate from chemical fertilizer that is not associated with human wastewater or livestock manure, 3) multiple contamination sources can affect a single well (including sources that were not tested), and 4) contamination sources can change over time (i.e., over the months since the original synoptic sampling events). A manifestation of these facts is that fecal markers were not detected in 60 of the 138 wells despite the presence of total coliforms or high nitrate during the synoptic sampling.

Conclusions

Human, bovine, and porcine fecal sources contributed to private well contamination, and human wastewater markers occurred most frequently. Septic systems and manure are common sources of the fecesborne microbes detected. Results from this objective identify fecal sources of contamination but not non-fecal sources, and not all wells were positive for a source-specific fecal marker.

Objective 3

Objective

Analyze private well samples collected for Objective 2 for genes specific to certain pathogens.

Approach: Sample collection and analysis

Samples collected for Objective 2 (n = 138) were tested for the fecesborne pathogens listed in Table 4 using genetic tests. Wells were randomly selected from those positive for total coliforms or high nitrate (NO_3^--N >10 mg/L). Sample collection and analysis are described in Objective 2 and Appendix 3.

Key findings

- Pathogens were detected in 66 of 138 wells (48%; Table 4). Some of the pathogens can only infect humans, while others can be passed between humans and animals ("zoonotic").
- Zoonotic pathogens were detected frequently. Because the same pathogen type can infect animals and humans, their source is unknown.
- The health risk associated with pathogen presence in private wells depends on the pathogen type, the concentration of pathogens in the well, the quantity of water consumed, the presence of water treatment, and the susceptibility of the individuals exposed.

Context and interpretation

Pathogen sources. Pathogen presence in private wells depends on proximity to fecal sources and whether the fecal sources contain pathogens (i.e., whether the humans or animals were infected). Some of the pathogens detected in these private wells only infect people and therefore originated in human wastewater. In most cases, however, the pathogen source was ambiguous because the particular pathogen can be found in fecal material from humans, livestock, or wildlife.

Regardless of the source, the pathogens detected are fecesborne and indicate fecal contamination. Combined with the wastewater and manure results in Objective 2, a total of 106 wells (79%) were positive for fecal microbes. The percentage of wells positive for fecal microbes does not represent the percentage of wells contaminated in the study area because wells tested for Objectives 2 and 3 were selected from wells that had previously tested positive for indicator bacteria or high nitrate.

Health risk. Pathogens in drinking water represent a potential risk of illness, and consumption of untreated groundwater (including drinking water from private wells) is recognized as a risk factor for waterborne disease (Craun et al. 2010; Wallender et al. 2014). Determining the level of risk associated with the pathogen measurements was beyond the scope of the study, though other studies provide context for these results. Pathogens were present in 16% of wells sampled in 41 North American studies (Hynds et al. 2014). Fewer pathogens (2 to 3) were included in those 41 studies than in the current study. Twenty pathogen tests were included by Borchardt et al. (2021) in Kewaunee County, and 32 of 131 private wells (24%) tested positive for a pathogen. Health risk from these pathogens was estimated to exceed the U.S. health benchmark for public drinking water, which is 1 infection per 10,000 people per year: per 10,000 Kewaunee County residents that drink private well water, 260 were estimated to become ill annually (Burch et al. 2021).

The pathogen tests are used for research and are not routinely available to homeowners, but total coliforms and *E. coli* are commonly used to assess the sanitary quality of private well water. Well samples negative for total coliforms have a high probability of being negative for pathogens as well (Stokdyk et al. 2020; Fout et al. 2017). In contrast, the presence of total coliforms in a sample does not necessarily indicate the presence of pathogens (Stokdyk et al. 2020; Fout et al. 2017), though it is indicative of microbiological contamination; Wisconsin DNR suggests protective measures when private wells test positive for indicator bacteria (WDNR 2017). The sanitary quality of well water can change, so regular testing has been recommended (Atherholt et al. 2015; Murphy et al. 2020; WDNR 2017).

Table 4. Pathogen occurrence in 138 private wells sampled in four events (34 or 35 wells per event).

	Number of positive wells				
Pathogen	April (n = 35)	August (n = 34)	November (n = 34)	March (n = 35)	Total (n = 138)
Campylobacter jejuni	0	3	0	0	3
Cryptosporidium hominis[a]	1	3	4	0	8
Cryptosporidium parvum	2	4	2	0	8
Cryptosporidium species	1	5	7	16	29
Giardia duodenalis assemblage B	0	0	0	1	1
Hepatitis E virus	0	0	0	0	0
Human adenovirus groups A-F[a]	2	0	0	0	2
Human enterovirus[a]	1	0	0	0	1
Human polyomavirus[a]	0	0	0	0	0
Norovirus genogroup I[a]	0	0	0	0	0
Norovirus genogroup II	0	1	0	1	2
Pathogenic *E. coli*	0	0	0	0	0
Rotavirus group A	3	0	4	2	9
Rotavirus group C	0	1	0	1	2
Salmonella	7	2	2	2	13
Shiga toxin 1-producing bacteria	0	1	0	0	1
Shiga toxin 2-producing bacteria	0	0	0	0	0
Any pathogen[b]	13	19	16	18	66

Note: While tests identified pathogen-specific genes, pathogen names are listed for clarity of presentation. Two genes were tested for rotavirus group A and *Salmonella*.

[a]Indicates pathogens that infect only humans; others can infect humans and animals.

[b]The number of positive wells for any pathogen does not equal the sum of individual pathogens because some wells were positive for multiple pathogens.

Strengths and limitations

The samples tested for pathogens were collected for Objective 2, so the additional pathogen analyses add information by building on the existing sample collection effort and cost. A significant strength of Objective 3 is that many pathogens were included (19 pathogen genetic tests), providing a diverse assessment of pathogen occurrence. Pathogen occurrence studies for groundwater typically include few pathogens (an average of 2 to 3; Hynds et al. 2014).

Like Objective 2, seasonal events were included so that wells were sampled throughout the year, and comparison of seasons is limited because there was a single sampling event for each. The tests used for Objective 3 identify pathogens by their genetic material (e.g., DNA) and are therefore very accurate, but the tests do not distinguish between living and dead pathogens. Finally, pathogen presence in private wells indicates the potential for health risk, but determining the specific risk of illness requires additional data.

Conclusions

The presence of pathogen genes in private well water indicates a potential but unquantified health risk. The pathogens may originate in human wastewater and livestock manure, but the specific source of pathogens was often unknown.

Objective 4

Objective

Assess well construction and geologic characteristics (e.g., well age, bedrock depth) that are related to well contamination.

Approach: Data and statistics

A variety of factors were examined for their relationships with well contamination. Well characteristics were obtained from well construction reports. Well siting data, like elevation and slope, were obtained from existing data sets using geographic information systems (GIS). Geologic factors were identified using well construction reports and geologic maps. Rainfall, groundwater depth, and groundwater recharge were characterized for the period preceding sample collection. Appendix 7 includes a complete list of risk factors.

Statistical tests identified associations among risk factors and well contamination by total coliforms, nitrate, and fecesborne microbes (Figure 11). Risk factors were related to two types of contaminant measurements, detection (yes or no) and concentration. Tests of association were performed separately for wells sampled in the November and April synoptic events; wells sampled for fecesborne microbes in the four seasonal events were analyzed together. Appendix 4 describes the statistical analyses. Tables 5 – 9 report the risk factors that were statistically identified and had a plausible association with contamination (factors not listed were not associated with contamination). In addition, Tables 10 – 12 report the probability of contamination at the minimum and maximum observed values of each factor, which illustrates the range of estimated contamination probabilities associated with the factor.

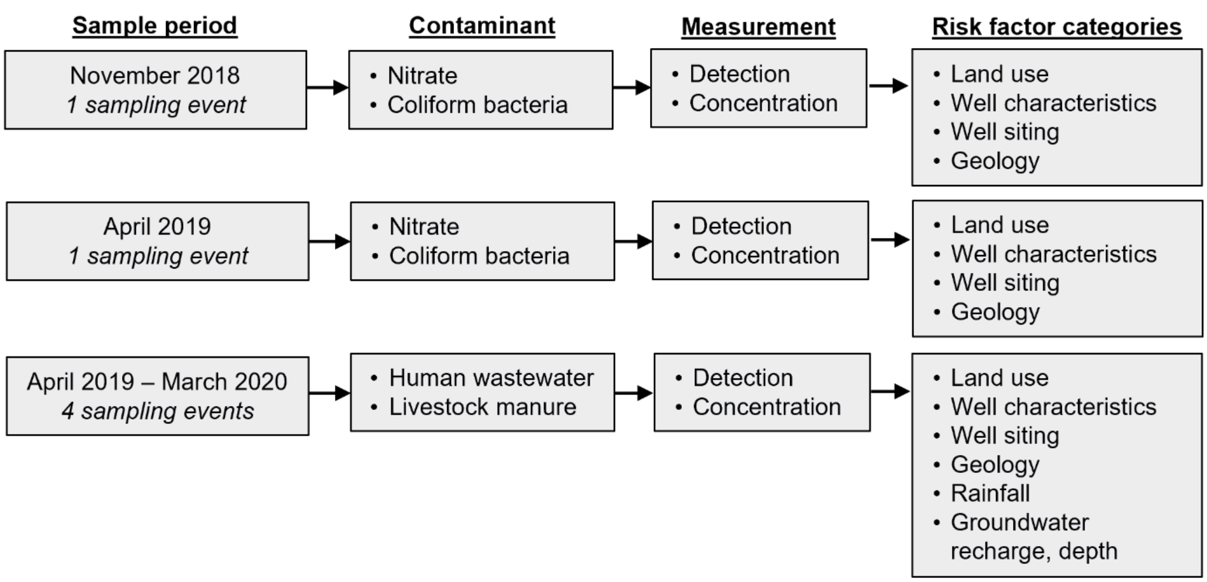

Figure 11. Organization of statistical tests that relate measurements of contaminants in private wells to contamination risk factors. For example, both the detection and concentration of nitrate in well water samples collected in November 2018 were related to well depth, a risk factor in the well characteristics category. Rainfall and groundwater were included with human wastewater and livestock manure markers because they varied across the 4 seasonal events, while samples for total coliforms and nitrate were collected over a short period (2 days) during which rainfall and groundwater varied little.

Key findings

- Contamination of private wells by nitrate, total coliforms, and fecesborne microbes was associated with well characteristics, well siting, geology, rainfall, and groundwater levels (Tables 5 – 9).
- The identified risk factors are related to contaminant transport (i.e., movement of the contaminant from the land surface to groundwater).
- Factors for nitrate, total coliforms, and fecesborne microbes can differ because they can behave differently when moving to groundwater and because their sources can differ.
- Contamination was greater for wells that were older, shallower, and had shorter casings (for example, Figure 12).
- Contamination was greater for wells completed in the fractured carbonate upper aquifer and wells that cross-connected the upper and lower aquifers.

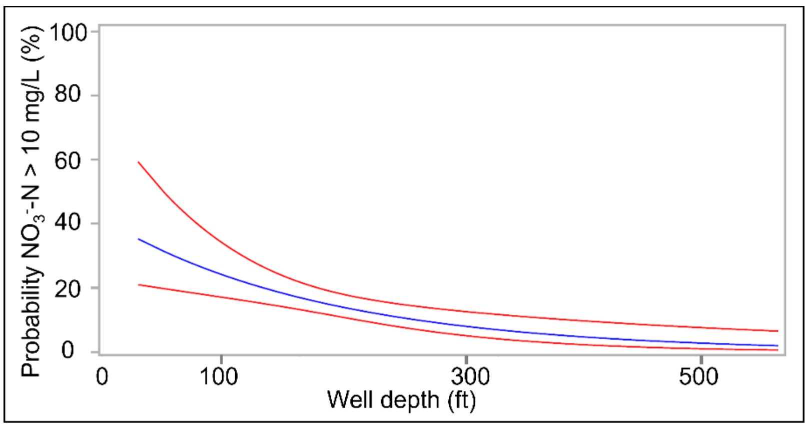

Figure 12. The probability of NO_3^--N exceeding 10 mg/L decreases as well depth increases. The probability is 35% at the shallowest well depths and 2% at the deepest (the data and pictured trend are for the April 2019 synoptic event). The blue line represents the estimated trend for the association; red lines are 95% confidence limits (range we are confident the true probabilities lie within).

Context and interpretation

<u>Well characteristics</u>. Well characteristics, like age and depth, have been identified as important factors for contamination in some studies (e.g., Allevi et al. 2013), while they were unimportant in other studies (e.g., Won et al. 2013). Differences in geologic settings may affect the importance of well characteristics. In Kewaunee County, for example, well characteristics were not often associated with contamination, likely because the geological characteristics of the aquifer are generally similar over the course of its depth (Borchardt et al. 2021). In contrast, well characteristics were associated with contamination in southwest Wisconsin, where the geology is complex and variable (Carter et al. 2011; Muldoon et al. 2021).

Well depth, casing depth, and length of casing into bedrock were associated with contamination by nitrate and total coliforms; casing length below water table was important for total coliforms but not nitrate. These well characteristics were inversely associated with contamination (e.g., contamination decreased as well depth increased). The effect of depth may reflect the dilution or dispersion (spreading out) of contaminants as they travel downward. Likewise, the concentration of human wastewater markers was greater when the depth to groundwater was shallower, as shallow depths produce shorter distances from septic systems to groundwater. In addition, contamination increased with well age, which may reflect deterioration or changes in well construction practices over time (e.g., well depth, grouting). Because well characteristics are correlated (e.g., deeper wells tend to have deeper well casing), the well characteristic most responsible for driving contamination is not easily distinguished. Nonetheless, results show that well characteristics were associated with contamination.

Geology. Geology is recognized as an important factor for groundwater contamination because water and contaminants move more readily through some materials than others. The geology of southwest Wisconsin includes various bedrocks and multiple aquifers (Carter et al. 2011; Muldoon et al. 2021). Two geologic factors were associated with private well contamination: topmost bedrock and geology at the well's open interval (the well length between the casing bottom and the bottom of the well). First, contamination, especially nitrate, was greatest where the Sinnipee Group was the topmost bedrock. The Sinnipee Group contains fractured carbonate rocks that allow rapid flow of water and contaminants. Second, contamination was greater for wells open to the upper aquifer, which is primarily comprised of the Sinnipee Group, while wells completed in the lower aquifer tended to be less contaminated. Wells that cross-connected the upper and lower aquifers (i.e., wells that draw water from both aquifers) also had greater contamination.

Bedrock depth. Bedrock depth is central to recent revisions to the Wisconsin Administrative Code that regulates manure application (Wis. Admin. Code § NR 151.075). The revisions apply to areas in eastern Wisconsin with fractured bedrock (Silurian dolomite) and shallow bedrock depth (less than 20 feet). As demonstrated by Borchardt et al. (2021) in Kewaunee County, bedrock depth is a primary factor for contamination of wells by nitrate, total coliforms, livestock manure, and human wastewater.

Interpreting the statistics

Three elements are used to interpret the statistics for Objectives 4 & 5:

1. The **p-value** describes the likelihood that the association is real, with lower values indicating higher likelihood. Only risk factors with a reasonable level of certainty (p-value less than 0.15) were included in Tables 5 - 18.

2. The **trend** describes the association between the risk factor and contamination. As the value of the risk factor increases (like well depths going from shallow to deep), contamination can either increase (positive trend) or decrease (negative trend).

3. The **probability of contamination** at the minimum and maximum observed values of each risk factor illustrates the range of estimated contamination probabilities associated with the risk factor (Tables 10 – 12 & 16 – 18).

Example: high nitrate in April

The **p-value** of less than 0.001 indicates that the association between well depth and high nitrate is likely real (Table 7). The **trend** is negative, so the **probability of contamination** decreases as well depth increases: from 35% at the shallowest well depths to 2% at the deepest (Table 10).

In comparison, the **trend** for well age and high nitrate is positive, so the **probability of contamination** is greatest (43%) for the oldest wells, which is greater than the probability for the shallowest wells.

However, bedrock depth was not consistently associated with contamination in southwest Wisconsin: bedrock depth was associated with total coliforms and human wastewater but not nitrate and livestock manure.

Why were there differences? Livestock manure contamination may have been unrelated to bedrock depth in this study because there were too few positive samples to identify a relationship. More samples were positive for total coliforms and human wastewater markers. Numerous samples were also positive for nitrate, so the absence of a relationship with bedrock depth may result from differences in the contaminants (microbes versus chemical) or from geological considerations. Wells located in the Sinnipee Group had greater nitrate contamination than wells in other geologic units, so bedrock *type* was important for nitrate contamination. The effect of bedrock depth may be less apparent because most wells had shallow bedrock depths, and there were few wells with deeper depths for comparison. For example, in Kewaunee County, Borchardt et al. (2021) observed that high nitrate was more likely for wells with bedrock depth of 20 feet or less, which included approximately half the wells in that study. In contrast, 85% of wells tested for this study had bedrock depth of 20 feet or less. Unlike microbes, nitrate is highly mobile, so the limited range in bedrock depth among the study wells may preclude the identification of a relationship.

<u>Well siting</u>. The well siting factors elevation, slope, and soil hydrologic group were also associated with contamination. The association with elevation may reflect variation in contamination by general location (e.g., uplands and river bottoms) or from specific topographic influences (e.g., steep ridges). Soil hydrologic group reflects the tendency for water to infiltrate to groundwater versus run off the surface (NRCS 1996), and slope may likewise affect the infiltration or runoff of water. As factors related to contaminant transport, slope and hydrologic soil group identify well siting conditions that may be prone to contamination. For example, nitrate contamination was associated with flatter slopes and poorly drained soils. The specific mechanisms by which the well siting factors may affect contamination are not always clear, but their significance indicates that factors related to contaminant transport are important.

Strengths and limitations

The statistical tests included many wells, many factors, and multiple contamination outcomes, providing a comprehensive assessment of factors associated with private well contamination.

These results identify statistical associations among contamination and risk factors. They do not identify cause and effect, though the factors identified do have plausible relationships with groundwater contamination.

Each risk factor was examined independently (without accounting for the effect of other factors), and some factors are likely to be intercorrelated. For example, the important well siting factors (slope, elevation, and soil group) may be correlated with land use practices or the underlying geology. Further evaluation of each important risk factor that accounts for the effect of other risk factors may refine our understanding of these relationships.

When a specific risk factor is associated with greater contamination, the finding applies to the three-county private wells as a group. For example, results indicate that high nitrate is more likely for shallow wells, but this does not mean that all wells that are shallow will have high nitrate. Risk factors should be interpreted in terms of probability of contamination, not as absolutes.

Conclusions

Private well water quality was associated with factors related to contaminant transport and groundwater vulnerability, including well characteristics, well siting, geology, and groundwater depth. It is unlikely that any single factor accounts for all private well contamination because many factors were associated with the presence and concentration of contaminants

Tables with important risk factors by sampling event: well characteristics, well siting, geology, rainfall, and groundwater levels

Note: Factors not listed were not associated with contamination, except when multiple risk factors of the same type were important (e.g., slope within 750, 1500, and 3000 feet of a well), only the one with the strongest association was listed.

Table 5. Geologic, well characteristic, and well siting risk factors associated with nitrate contamination for the November synoptic event.

Contamination	Risk factor	P-value[a]	Trend[b]
Probability of high nitrate	Geology		
	Open interval geology	<0.001	Note 1
	Topmost bedrock	0.043	Note 2
	Well characteristics		
	Casing depth	0.004	Negative
	Casing length into bedrock	0.008	Negative
	Groundwater depth at construction	0.060	Negative
	Well age	<0.001	Positive
	Well depth	0.015	Negative
	Well siting		
	Slope, mean within 3000 ft	<0.001	Negative
	Soil hydrologic group	0.012	Note 3
	Well elevation	0.076	Positive
Nitrate concentration	Geology		
	Open interval geology	0.003	Note 4
	Topmost bedrock	0.002	Note 5
	Well characteristics		
	Casing depth	0.045	Negative
	Casing length into bedrock	0.037	Negative
	Groundwater depth at construction	0.101	Negative
	Well age	<0.001	Positive
	Well depth	0.129	Negative
	Well siting		
	Slope, mean within 3000 ft	<0.001	Negative
	Soil hydrologic group	0.024	Note 6
	Well elevation	0.095	Positive

[a]P-value ranges from 0 to 1 and indicates the likelihood that the association is real, with lower values indicating higher likelihood. All risk factors included in the table have evidence for an association with contamination ($p<0.15$). By convention, p-values <0.05 are considered formally significant.

[b]A positive trend indicates that contamination increases as the value of the risk factor increases; a negative trend indicates that contamination increases as the value of the risk factor decreases.

Notes for risk factor trends:

1. Greater probability of contamination for wells in the upper aquifer and wells cross-connecting aquifers
2. Greater probability of contamination for Sinnipee and sand/gravel
3. Greatest probability of contamination for group C soils (poorly drained)
4. Greater concentrations for wells cross-connecting aquifers; lower concentrations for wells completed in the lower aquifer
5. Greater concentrations for Sinnipee
6. Greater concentrations for group C soils (poorly drained)

Table 6. Geologic, well characteristic, and well siting risk factors associated with total coliforms contamination for the November synoptic event.

Contamination	Risk factor	P-value[a]	Trend[b]
Probability of total coliforms detection	Geology		
	Bedrock depth	0.081	Negative
	Topmost bedrock	0.015	Note 1
	Well characteristics		
	Casing length into bedrock	0.063	Negative
	Well age	<0.001	Positive
	Well siting		
	Soil hydrologic group	0.023	Note 2
Total coliforms concentration	Well siting		
	Slope, mean within 750 ft	<0.001	Positive
	Soil hydrologic group	0.039	Note 3
	Well elevation	0.020	Negative

[a,b]See footnotes for Table 5.

Notes for risk factor trends:

1. Lower probability of contamination for wells completed in sand/gravel
2. Lower probability of contamination for group A soils (very well drained)
3. Greater concentrations for group B soils (well drained)

Table 7. Geologic, well characteristic, and well siting risk factors associated with nitrate contamination for the April synoptic event.

Contamination	Risk factor	P-value[a]	Trend[b]
Probability of high nitrate	Geology		
	Open interval geology	<0.001	Note 1
	Topmost bedrock	0.026	Note 2
	Well characteristics		
	Casing depth	<0.001	Negative
	Casing length into bedrock	<0.001	Negative
	Groundwater depth at construction	0.005	Negative
	Well age	<0.001	Positive
	Well depth	<0.001	Negative
	Well siting		
	Slope, mean within 3000 ft	<0.001	Negative
	Soil hydrologic group	<0.001	Note 3
	Well elevation	0.057	Positive
Nitrate concentration	Geology		
	Open interval geology	<0.001	Note 4
	Topmost bedrock	<0.001	Note 5
	Well characteristics		
	Casing depth	<0.001	Negative
	Casing length into bedrock	0.001	Negative
	Groundwater depth at construction	0.001	Negative
	Well age	0.006	Positive
	Well depth	0.001	Negative
	Well siting		
	Slope, mean within 3000 ft	<0.001	Negative
	Soil hydrologic group	0.001	Note 6
	Well elevation	0.003	Positive

[a,b]See footnotes for Table 5.

Notes for risk factor trends:

1. Greater probability of contamination for wells completed in the upper aquifer and sand/gravel
2. Greater probability of contamination for Sinnipee, sand/gravel, and Maquoketa
3. Greater probability of contamination for soil groups C (poorly drained) and A (very well drained)
4. Greater concentrations for wells open to the upper aquifer; lower concentrations for wells open to the lower aquifer
5. Greatest concentrations for Sinnipee
6. Greatest concentrations for soil group C (poorly drained)

Table 8. Geologic, well characteristic, and well siting risk factors associated with total coliforms contamination for the April synoptic event.

Contamination	Risk factor	P-value[a]	Trend[b]
Probability of total coliforms detection	Well characteristics		
	Casing depth	0.048	Negative
	Casing length below water table	0.032	Negative
	Casing length into bedrock	0.022	Negative
	Well age	<0.001	Positive
	Well depth	0.114	Negative
	Well siting		
	Slope at well	0.068	Positive
	Soil hydrologic group	0.083	Note 1
Total coliforms concentration	Geology		
	Open interval geology	0.087	Note 2
	Well characteristics		
	Casing length below water table	0.065	Negative
	Open interval length	0.067	Positive
	Well depth	0.148	Positive
	Well siting		
	Slope at well	0.009	Negative

[a,b]See footnotes for Table 5.

Notes for risk factor trends:

1. Lowest probability of contamination for soil group A (very well drained)

2. Greater concentrations for wells that cross-connect aquifers; lower concentrations for wells completed in the upper aquifer

Table 9. Geologic, well characteristic, well siting, and hydrologic risk factors associated with human and livestock fecal markers.

Contamination	Risk factor	P-value[a]	Trend[b]
Human wastewater marker, probability of detection	Well siting		
	Slope, mean within 750 ft	0.081	Negative
	Well elevation	0.050	Positive
	Rainfall		
	Rainfall, 7-day antecedent, cumulative	0.058	Positive
Human wastewater marker concentration	Geology		
	Bedrock depth	0.061	Negative
	Well characteristics		
	Well age	0.104	Positive
	Well depth	0.147	Negative
	Groundwater		
	Groundwater depth, 21-day antecedent, minimum	0.090	Negative
	Rainfall		
	Rainfall, 2-day antecedent, cumulative	0.024	Note 1
Livestock manure marker, probability of detection	Geology		
	Topmost bedrock	0.122	Note 2
	Well characteristics		
	Open interval length	0.128	Negative

[a,b]See footnotes for Table 5.

Notes for risk factor trends:

1. Greater concentrations when there was rainfall of any amount 2-days prior to sample collection
2. Greater probability of contamination for Ancell (St. Peter sandstone)

Table 10. Summary of contamination probability for high nitrate and total coliforms across the range of geology and well risk factors for the November synoptic event.

Contamination	Risk factor (units)	Risk factor min. value	Probability of contamination at risk factor min.	Risk factor max. value	Probability of contamination at risk factor max.
Probability of high nitrate	Geology				
	Open interval geology	Note 1	4%	Note 1	26%
	Topmost bedrock	Note 2	3%	Note 2	19%
	Well characteristics				
	Casing depth (feet)	15	30%	434	<1%
	Casing length into bedrock (feet)	-2[a]	26%	370	1%
	Groundwater depth at construction (feet)	2	23%	460	3%
	Well age (years)	<1	3%	71	55%
	Well depth (feet)	54	30%	548	2%
	Well siting				
	Slope, mean within 3000 ft (percent)	2	65%	74	2%
	Soil hydrologic group	Note 3	9%	Note 3	20%
	Well elevation (feet above sea level)	631	8%	1317	27%
Probability of total coliforms detection	Geology				
	Bedrock depth (feet)	0	38%	151	10%
	Topmost bedrock	Note 4	6%	Note 4	36%
	Well characteristics				
	Casing length into bedrock (feet)	-2[a]	41%	370	14%
	Well age (years)	<1	15%	71	73%
	Well siting				
	Soil hydrologic group	Note 5	8%	Note 5	36%

Min., Minimum; Max., Maximum

[a]Negative value indicates that the casing was finished above the bedrock.

Notes

1. Probability of contamination for Upper aquifer = 26%, cross-connecting aquifers = 20%, lower aquifer = 4%
2. Probability of contamination for Sinnipee = 19%, sand/gravel = 18%, other units = 3%
3. Probability of contamination for Group C soils (poorly drained) = 20%, other soil groups = 9%
4. Probability of contamination for sand/gravel = 6%, other units = 36%
5. Probability of contamination for Group A soils (very well drained) = 8%, other soil groups = 36%

Table 11. Summary of contamination probability for high nitrate and total coliforms across the range of geology and well risk factors for the April synoptic event.

Contamination	Risk factor (units)	Risk factor min. value	Probability of contamination at risk factor min.	Risk factor max. value	Probability of contamination at risk factor max.
Probability of high nitrate	Geology				
	Open interval geology	Note 1	5%	Note 1	36%
	Topmost bedrock	Note 2	5%	Note 2	18%
	Well characteristics				
	Casing depth (feet)	20	29%	380	1%
	Casing length into bedrock (feet)	-6[a]	28%	368	1%
	Groundwater depth at construction (feet)	0	24%	410	3%
	Well age (years)	1	6%	78	43%
	Well depth (feet)	30	35%	560	2%
	Well siting				
	Slope, mean within 3000 ft (percent)	1	64%	73	2%
	Soil hydrologic group	Note 3	6%	Note 3	20%
	Well elevation (feet above sea level)	618	8%	1278	22%
Probability of total coliforms detection	Well characteristics				
	Casing depth (feet)	20	17%	380	4%
	Casing length below water table (feet)	-334[a]	41%	215	5%
	Casing length into bedrock (feet)	-6[a]	19%	368	3%
	Well age (years)	1	5%	78	36%
	Well depth (feet)	30	19%	560	5%
	Well siting				
	Slope at well (percent)	0	12%	109	28%
	Soil hydrologic group	Note 4	7%	Note 4	16%

Min., Minimum; Max., Maximum

[a]Negative value indicates that the casing was finished above the bedrock or water table.

Notes

1. Probability of contamination for upper aquifer = 35%, sand/gravel = 36%, cross-connecting aquifers = 14%, lower aquifer = 5%
2. Probability of contamination for Maquoketa = 18%, Sinnipee = 17%, sand/gravel = 16%, other units = 5%
3. Probability of contamination for Group C soils (poorly drained) = 20%, Group A soils (very well drained) = 17%, other soil groups = 6%
4. Probability of contamination for Group A soils (very well drained) = 7%, other soil groups = 16%

Table 12. Summary of contamination probability for human and livestock fecal markers across the range of geology and well risk factors.

Contamination	Risk factor (units)	Risk factor min. value	Probability of contamination at risk factor min.	Risk factor max. value	Probability of contamination at risk factor max.
Human fecal microbe, probability of detection	Well siting				
	Slope, mean within 750 ft (percent)	3	62%	93	24%
	Well elevation (feet above sea level)	654	25%	1251	72%
	Rainfall				
	Rainfall, 7-day antecedent, cumulative (inches)	0	39%	2	64%
Livestock fecal microbe, probability of detection	Geology				
	Topmost bedrock	Note 1	25%	Note 1	47%
	Well characteristics				
	Open interval length (feet)	4	40%	462	6%

Min., Minimum; Max., Maximum

Note 1. Contamination probability was greater for the Ancell (St. Peter sandstone) (47%) than for others (25%)

Objective 5

Objective

Identify land use factors and potential contamination sources (e.g., number of nearby septic systems, distance to an agricultural field) related to well contamination.

Approach: Data and statistics

Land use surrounding wells was examined for relationships with well contamination. Septic systems were identified from county records, farms were identified from aerial imagery, and cultivated land was identified using data from U.S. Department of Agriculture (Muldoon et al. 2021). Land use was characterized within 750, 1500, and 3000 feet of each well, including the number of septic systems (all types, including holding tanks), number of drainfield septic systems (only those designed to release effluent), and the area of cultivated land. In addition, each well's proximity (i.e., closest distance) to contamination sources was determined. For example, the distance from each well to the nearest farm was determined. Appendix 7 includes a complete list of risk factors.

Statistical modeling identified associations among contamination and land use risk factors as described in Objective 4. Technical procedures are described in Borchardt et al. (2021) and are summarized in Appendix 4. Tables 13 – 15 report the risk factors that were statistically identified and had a plausible association with contamination. In addition, Tables 16 – 18 report the probability of contamination at the minimum and maximum observed values of each factor, which illustrates the range of estimated contamination probabilities associated with the factor.

Key findings

- Agricultural land use was associated with contamination of wells by nitrate, total coliforms, and livestock manure markers.
- Septic systems were associated with contamination by human wastewater markers.
- Factors for nitrate, total coliforms, and fecesborne microbes can differ because their sources can differ and because they can behave differently when moving to groundwater.

Context and interpretation

Nitrate and total coliforms. Agricultural land use was associated with contamination by nitrate and, to a lesser extent, total coliforms. The area of cultivated land around a well, the distance to cultivated land, and the distance to the nearest livestock farm were associated with nitrate and/or total coliforms (for example, Figure 13). However, septic systems were not associated with an increased probability of contamination by nitrate or total coliforms. For private wells in Kewaunee County, Borchardt et al. (2021) also found that agricultural land use, but not septic systems, was associated with contamination by nitrate and total coliforms.

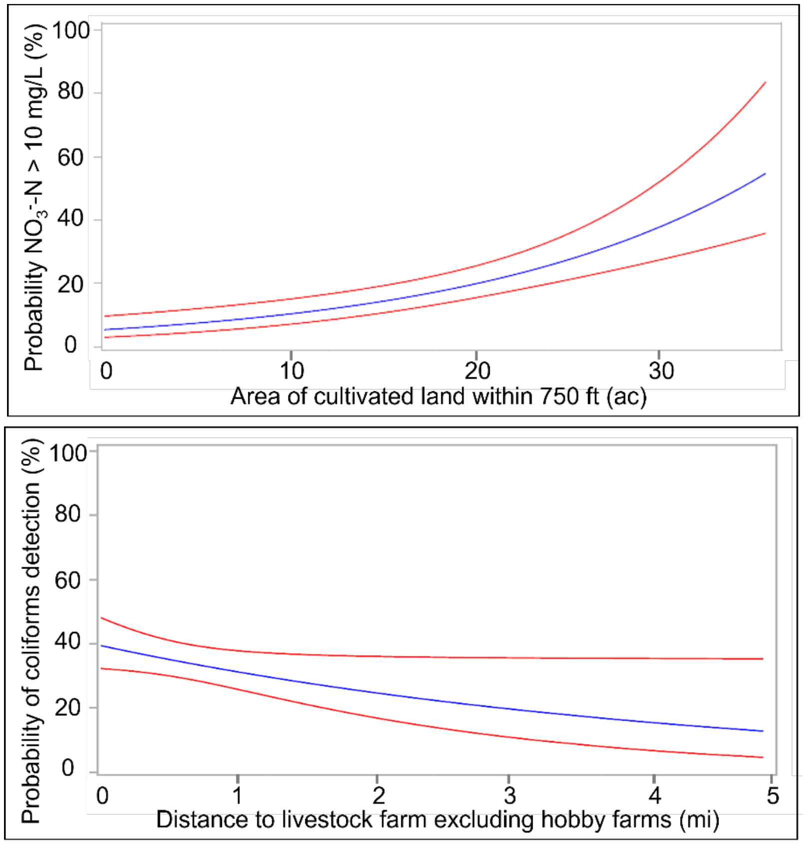

Figure 13. Top panel: The probability of NO_3^--N exceeding 10 mg/L increases as the area of cultivated land within 750 feet of the well increases (the 750-foot radius contains 40 acres (ac)). The probability is 5% if there are 0 acres and 55% if there are 37 acres (the data and pictured trend are for the November 2018 synoptic event). Bottom panel: The probability of total coliforms detection increases if wells are closer to a livestock farm excluding hobby farms (in miles (mi)). The probability is 13% at the longest distance and 38% at the shortest distance (the data and pictured trend are for the November 2018 synoptic event). The blue line represents the estimated trend for the association; red lines are 95% confidence limits (range we are confident the true probabilities lie within).

Human wastewater. Sixty-four of 138 wells (46%) were positive for human wastewater markers, and the number of nearby septic systems and the distance to the nearest septic system drainfield were associated with this contamination (Table 15). For example, the probability of contamination was greater if the nearest neighbor's drainfield septic system was closer (Figure 14; distances excluded septic systems on the same parcel as the well). Likewise, the probability of contamination increased from 44% (when one septic system was within 750 feet of the well) to a probability of 79% (when 18 septic systems were within 750 feet; counts included systems on the same parcel as the well). The fact that human wastewater contaminates wells when only a few septic systems are nearby illustrates the vulnerability of groundwater, especially when groundwater depths are shallow (Table 9).

Initially there appeared to be an association of human wastewater contamination with land-applied waste. However, the distances of the association were over 12 miles, much farther than groundwater is known to flow in the region, and the association was non-existent or weak at plausible distances. The association between human wastewater contamination and septic systems was stronger, consistent with the fact that numerous septic systems were located between these fields and study wells. Also, the volume of land-applied waste was much less than the volume of septic system effluent. Septic systems are a consistent fecal source because they have fixed locations and continually release effluent.

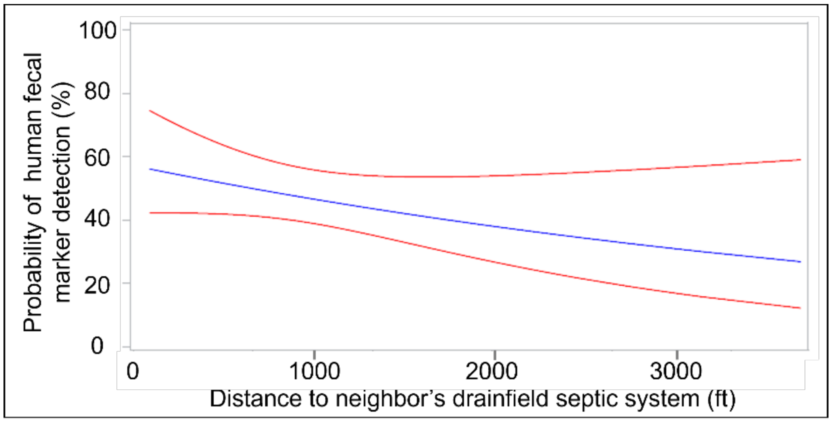

Figure 14. The probability of detecting a human fecal marker increases if wells are closer to a neighbor's drainfield septic system (in feet (ft)). The probability is 27% at the longest distance and 56% at the shortest distance (distances exclude septic systems on the same parcel as the well). The blue line represents the estimated trend for the association; red lines are 95% confidence limits (range we are confident the true probabilities lie within).

Many factors can affect groundwater quality.

Groundwater quality is affected by factors related to the **transport** and **sources** of contaminants.

Objective 4 examined factors related to contaminant **transport**--that is, the tendency of contaminants to reach groundwater or enter wells.

The land use factors examined for **Objective 5** represent potential contaminant **sources**--places where contaminants may originate.

Some factors may be related. For example, geology may be correlated with slope or land use. Because many **transport** and **source** factors can play a role, individual factors may be best considered in the context of the others.

Objectives 4 & 5 can be a tool to understand the **source** and **transport** factors related to private well contamination:

- Factors in **Objective 4** may help describe areas or conditions more or less prone to contamination.
- Factors in **Objective 5** describe relationships between contamination and potential sources.

<u>Livestock manure</u>. In contrast to septic systems, livestock manure is an intermittent fecal source because the timing, location, and quantity of manure on the landscape vary with application and grazing schedules. Because manure application data were not available, we used general assessments of agricultural land (cultivated land and farm locations), which do not always correspond to manure presence. Associations among agricultural land use and the *detection* (i.e., the presence) of manure contamination were not identified, but associations were identified with the *concentration* of livestock manure markers. Manure is not always present on all fields, which complicates the identification of associations based on presence/absence (i.e., detection). In contrast, when manure markers were present in wells, concentrations were associated with agricultural land use. Manure markers must be present in a well to measure their concentration, and the presence of manure markers in a well indicates that manure was nearby. Borchardt et al. (2021) made the same observation for private wells in Kewaunee County, as that study also identified associations among agricultural land use and the concentration (but not presence) of manure markers.

Strengths and limitations

The statistical tests included many wells, many factors, and multiple contamination outcomes, providing a comprehensive assessment of factors associated with private well contamination.

These results identify statistical associations among contamination and risk factors. They do not identify cause and effect, though the factors identified do have plausible relationships with groundwater contamination.

Each risk factor was examined independently (without accounting for the effect of other factors), and some factors are likely to be intercorrelated. Further evaluation of each important risk factor that accounts for the effect of other risk factors may refine our understanding of these relationships.

The relationship between risk factors and contamination are specific and quantitative. For example, the relationships show how contamination increases for each additional septic system near a well or for each additional acre of cultivated land near a well. When a specific risk factor is associated with greater contamination, the finding applies to the three-county private wells as a group. For example, results indicate that high nitrate is more likely for wells near cultivated land, but this does not mean that all wells that are near cultivated land will have high nitrate. Risk factors should be interpreted in terms of probability of contamination, not as absolutes.

Conclusions

Land use surrounding private wells was associated with contamination. Contamination by nitrate, total coliforms, and livestock manure markers was associated with agricultural land use. Contamination by human wastewater markers was associated with septic systems. The relationships between these factors and contamination may inform efforts to address water quality.

Tables with important risk factors by sampling event: land use

Factors not listed were not associated with contamination, except: when multiple risk factors of the same type were important (e.g., the area of cultivated land within 750, 1500, and 3000 feet of a well), only the one with the strongest association was listed.

Table 13. Land use risk factors associated with nitrate and total coliforms contamination for the November synoptic event.

Contamination	Risk factor	P-value[a]	Trend[b]
Probability of high nitrate	Agriculture		
	Cultivated land, area within 750 ft	<0.001	Positive
	Cultivated land, distance to nearest	0.114	Negative
	Livestock farms excluding hobby farms, distance to nearest	0.026	Negative
Nitrate concentration	Agriculture		
	Cultivated land, area within 750 ft	<0.001	Positive
	Cultivated land, distance to nearest	<0.001	Negative
	Livestock farms excluding hobby farms, distance to nearest	<0.001	Negative
Probability of total coliforms detection	Agriculture		
	Livestock farms excluding hobby farms, distance to nearest	0.050	Negative

[a]P-value ranges from 0 to 1 and indicates the likelihood that the association is real, with lower values indicating higher likelihood. All risk factors included in the table have evidence for an association with contamination ($p<0.15$). By convention, p-values <0.05 are considered formally significant.

[b]A positive trend indicates that contamination increases as the value of the risk factor increases; a negative trend indicates that contamination increases as the value of the risk factor decreases.

Table 14. Land use risk factors associated with nitrate contamination for the April synoptic event; no land use risk factors were identified for total coliforms in April.

Contamination	Risk factor	P-value[a]	Trend[b]
Probability of high nitrate	Agriculture		
	Cultivated land, area within 750 ft	<0.001	Positive
	Cultivated land, distance to nearest	0.022	Negative
	Livestock farms excluding hobby farms, distance to nearest	0.007	Negative
Nitrate concentration	Agriculture		
	Cultivated land, area within 750 ft	<0.001	Positive
	Cultivated land, distance to nearest	<0.001	Negative
	Livestock farms excluding hobby farms, distance to nearest	<0.001	Negative

[a,b]See footnotes for Table 13.

Table 15. Land use risk factors associated with contamination by human and livestock fecal markers.

Contamination	Risk factor	P-value[a]	Trend[b]
Human wastewater marker, probability of detection	Septic systems		
	Septic systems, count within 750 ft	0.039	Positive
	Drainfield septic systems, distance to nearest	0.142	Negative
Human wastewater marker concentration	Septic systems		
	Drainfield septic systems, count within 1500 ft	0.034	Positive
Livestock manure marker concentration	Agriculture		
	Cultivated land, area within 3000 ft	0.016	Positive
	Cultivated land, distance to nearest	0.130	Negative
	Livestock farms excluding hobby farms, distance to nearest	0.045	Negative

[a,b]See footnotes for Table 13.

Table 16. Summary of contamination probability for high nitrate and total coliforms across the range of land use risk factors for the November synoptic event.

Contamination	Risk factor (units)	Risk factor min. value	Probability of contamination at risk factor min.	Risk factor max. value	Probability of contamination at risk factor max.
Probability of high nitrate	Agriculture				
	Cultivated land, area within 750 ft (acres)	0	5%	37	55%
	Cultivated land, distance to nearest (feet)	0	42%	2050	<1%
	Livestock farms excluding hobby farms, distance to nearest (feet)	26	22%	26015	1%
Probability of total coliforms detection	Agriculture				
	Livestock farms excluding hobby farms, distance to nearest (feet)	26	38%	26015	13%

Min., Minimum; Max., Maximum

Table 17. Summary of contamination probability for high nitrate across the range of land use risk factors for the April synoptic event.

Contamination	Risk factor (units)	Risk factor min. value	Probability of contamination at risk factor min.	Risk factor max. value	Probability of contamination at risk factor max.
Probability of high nitrate	Agriculture				
	Cultivated land, area within 750 ft (acres)	0	5%	38	61%
	Cultivated land, distance to nearest (feet)	0	21%	1234	1%
	Livestock farms excluding hobby farms, distance to nearest (feet)	35	20%	23191	2%

Min., Minimum; Max., Maximum

Table 18. Summary of contamination probability for human wastewater markers across the range of land use risk factors.

Contamination	Risk factor (units)	Risk factor min. value	Probability of contamination at risk factor min.	Risk factor max. value	Probability of contamination at risk factor max.
Human fecal microbe, probability of detection	Septic systems				
	Septic systems, count within 750 ft (count)	1	44%	18	79%
	Drainfield septic systems, distance to nearest (feet)	89	56%	3662	27%

Min., Minimum; Max., Maximum

Conclusions

The study assessed the extent and sources of private well water contamination in southwest Wisconsin. The percentage of study wells with total coliforms or high nitrate was generally greater than statewide percentages. Human wastewater and livestock manure contributed to private well contamination, and pathogen genes were also detected. The study identified many factors that were associated with private well contamination, including land use, geology, and well characteristics. The factors will be further examined using sophisticated statistical approaches to provide additional insights that will be reported in a scientific journal. By assessing the extent, sources, and factors related to private well contamination, the study provides a detailed characterization of private well drinking water quality for the residents of southwest Wisconsin.

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Appendices

Appendix 1: Description of total coliforms, *E. coli*, and nitrate

Total coliforms, *E. coli*, and nitrate were selected to determine the extent of contamination (Objective 1) because they are standard tests for drinking water quality that are readily available and amenable to the testing of many samples in a short period. Total coliforms are a group of bacteria that include *E. coli*, and both are used as indicators of water sanitary quality (USEPA 2022). Total coliform bacteria found in groundwater originate from both fecal and nonfecal sources and are therefore a general indicator of sanitary quality, while *E. coli* are generally associated with fecal sources and therefore indicate fecal pollution (USEPA 2022). Most total coliform bacteria and *E. coli* are not pathogenic (they do not cause illness), so they are indicative of potential issues of sanitary quality but not necessarily of health risk (USEPA 2022). The maximum contaminant level goal for these bacteria is zero per 100 mL (that is, any detection of these bacteria is an exceedance of the goal; USEPA 2022). Nitrate in groundwater originates from fecal material (e.g., wastewater or manure), and unlike bacteria, it also originates from chemical fertilizers. Agricultural sources of nitrogen, like manure and fertilizer, exceed human waste sources in the three counties (Byrnes et al. 2020). Low levels of nitrate can also occur naturally, while concentrations greater than 1 to 3 mg NO_3^--N per L typically indicate anthropogenic influence, like fertilizers, manure, and wastewater (Luczaj and Masarik 2015; Madison and Brunett 1985). The maximum contaminant level for nitrate is 10 mg NO_3^--N per L, and chronic exposure to high nitrate levels can result in adverse health outcomes (USEPA 2022; WI DNR 2010). The maximum contaminant level goals for total coliforms, *E. coli*, and nitrate are from the U.S. National Primary Drinking Water Standards and apply only to public wells, but they provide public health benchmarks and are consistent with state groundwater quality standards (WDNR 2010; WDNR 2017; WDNR 2021).

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Appendix 2: Geology of the study area

Bedrock in the study area consists of a thick package of sedimentary rocks that outcrop in steep-sided stream valleys and hillslopes (Figures A1 and A2). The Sinnipee Group, which consists of the Galena, Decorah, and Platteville Formations, is the uppermost bedrock unit in the majority of the study area and forms a broad upland plateau south of Military Ridge (Figure A1). The younger Maquoketa Shale and Silurian dolomite are restricted to scattered "mounds" in the area. A conceptual model that includes two groundwater systems (upper and lower aquifers) was used for this study. The Sinnipee Group rocks make up the "upper aquifer" in the study area and are separated from the underlying St. Peter Sandstone by the Glenwood Shale, which acts as an aquitard and limits the downward migration of groundwater. The "lower aquifer" consists of the St. Peter Sandstone, the Prairie du Chien Group, the Trempealeau Group containing the Jordan sandstone and the St. Lawrence dolomite, and underlying sandstones of Cambrian age. The bedrock units comprising the "lower aquifer" are exposed north of Military Ridge and in the larger stream valleys south of Military Ridge. Carbonate bedrock is within 50 feet of the surface in much of the study area (Figure A3).

Except on the steep sides of valleys, the bedrock units are capped by unconsolidated surficial deposits (Figure A2). Where carbonate rocks are the uppermost bedrock unit, the Rountree Formation is sometimes present directly atop the bedrock. The Rountree consists of the residual weathering products from dissolution of the underlying carbonates, and the texture varies from clayey to sandy clay. Quaternary sediments above the Rountree consist primarily of wind-blown loess on the bedrock uplands. Colluvium and rare landslide deposits occur over bedrock on the valley sides. Alluvium, consisting of sand and gravel, occurs in the valley bottoms (Carson 2012).

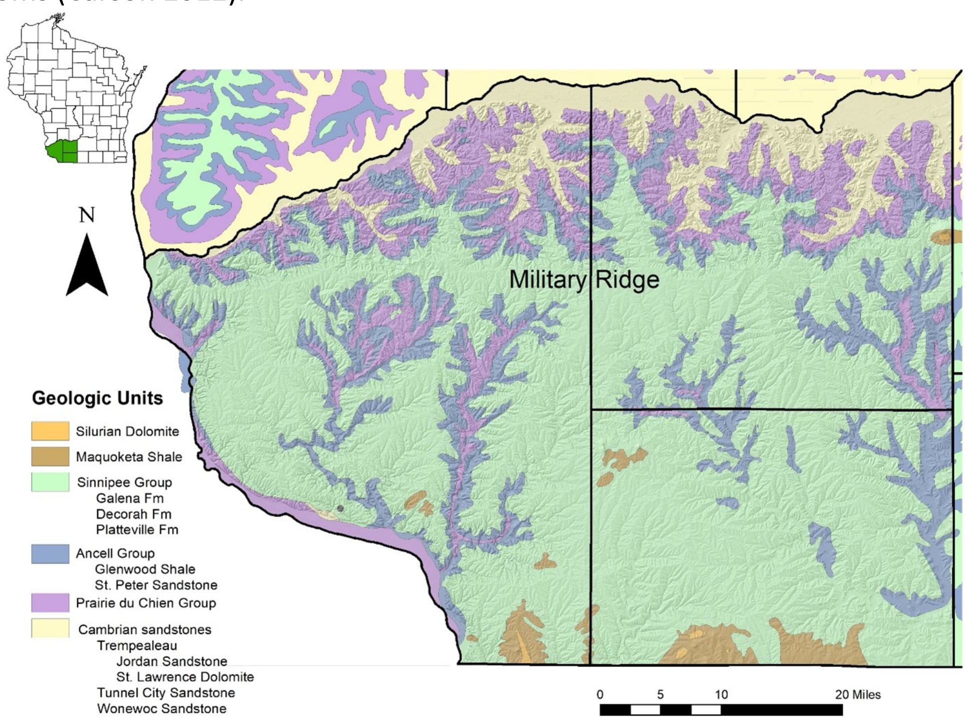

Figure A1. Bedrock geologic map of the study area (from Mudrey et al. 1982).

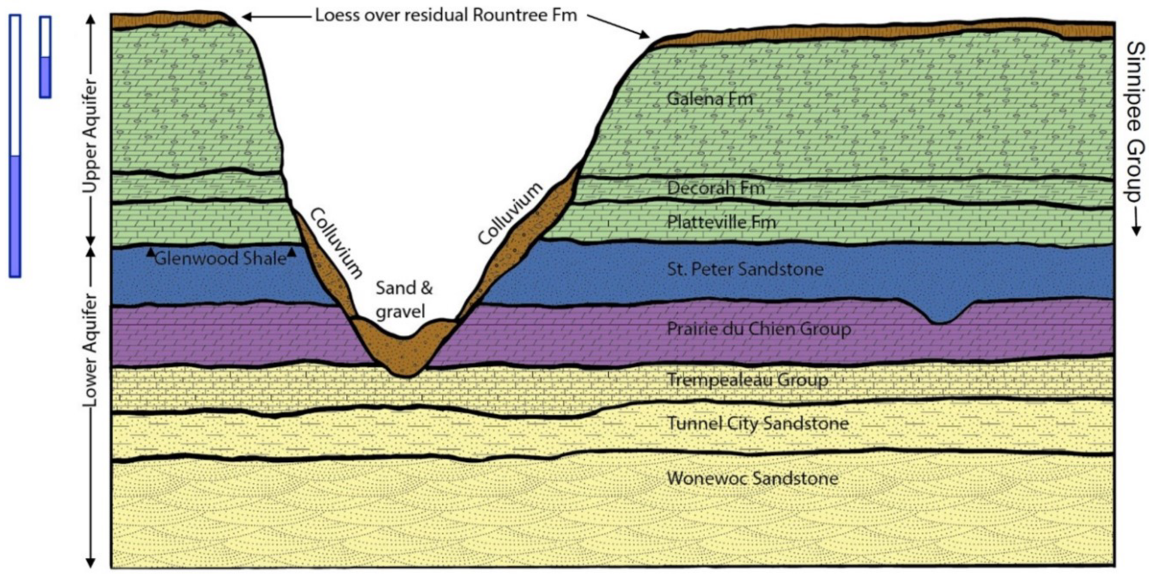

Figure A2. Cross section illustrating both surficial and bedrock geologic units as exposed in a typical stream valley in the study area; colors are similar to those in the bedrock geologic map in Figure A1. Diagrams to the left show the relationship of the upper and lower aquifers that are separated by the Glenwood Shale. Water levels in deep wells finished in the lower aquifer can stand far below water levels in shallower wells finished in the upper aquifer, as illustrated at the left. The shale is typically only a few feet thick and is too thin to show as a separate unit in this diagram.

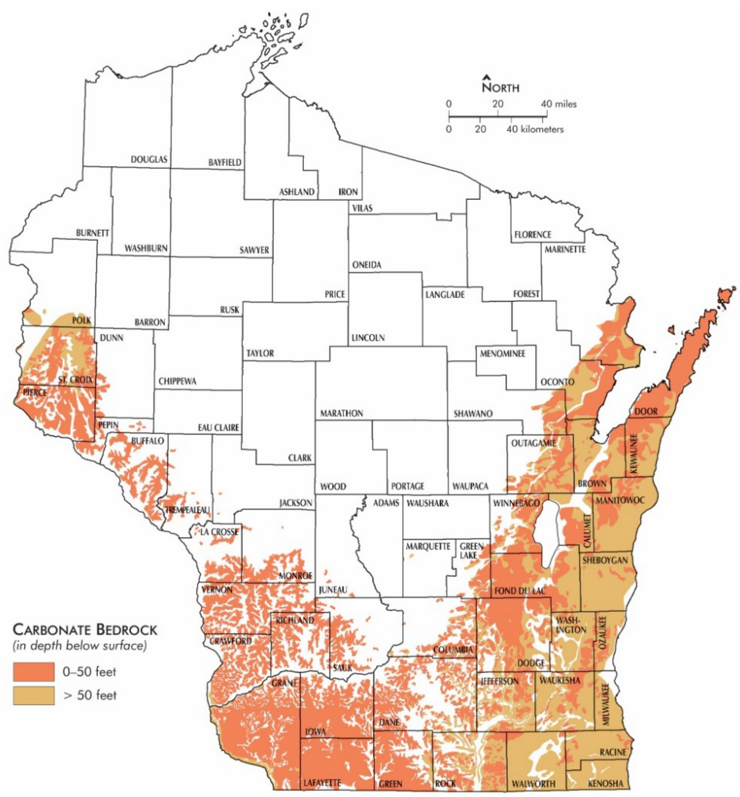

Figure A3. Shallow carbonate bedrock in Wisconsin (WGNHS 2009).

Table A1. Brief description of geologic units and their distribution in the study area (youngest to oldest).

Geologic Name	Composition	Hydrogeologic function	Geographic extent
Sand and gravel	sand and gravel	aquifer	floodplains of the Wisconsin and Mississippi Rivers and tributary streams; valley bottoms
Silurian Dolomite	dolomite	not an aquifer in this region	present only at Blue Mounds in Iowa County; not present elsewhere in the SWIGG counties
Maquoketa Shale	shale	aquitard	present only in mounds at Blue Mounds in Iowa County, Belmont Mound near Platteville, and isolated mounds in southern Grant and Lafayette Counties
Galena Dolomite	dolomite	aquifer	caps uplands south of Military Ridge; eroded away in river and stream valleys; in the Sinnipee Group
Decorah Shale	shale/ dolomite	possible aquitard	present in subsurface over most of region; eroded away in stream/river valleys; in the Sinnipee Group
Platteville Dolomite	dolomite	aquifer	present over most of region; eroded away in stream and river valleys; in the Sinnipee Group
Glenwood Shale	shale	aquitard	present in most of region; eroded away in stream and river valleys; can be inches to a few feet thick
St. Peter Sandstone	sandstone	aquifer	present throughout region; eroded away in stream and river valleys; has irregular unconformable base
Prairie du Chien Group	dolomite/ limestone	aquifer	present throughout region; eroded away in stream and river valleys
Jordan Sandstone	sandstone	aquifer	present throughout region; eroded away in stream and river valleys
St Lawrence Formation	dolomite	possible aquitard	present throughout region; eroded away in stream and river valleys
Cambrian Sandstones	sandstone	aquifer	sandstones of the Tunnel City, Wonewoc, and Mount Simon Formations; present throughout region

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Appendix 3: Sample collection and laboratory methods

For Objective 1, homeowners were instructed to collect water from a tap without treatment, sterilize the tap with flame or alcohol, and run water for 5 minutes prior to filling bottles. Coliforms and *E. coli* were measured within 30 hours of sample collection using Colilert Quanti-Trays (Idexx). Nitrate was measured by the cadmium reduction method on a Lachat QuikChem 5000 (limit of detection was 0.1 mg/L).

For Objectives 2 and 3, water from an outdoor tap or pressure tank was collected in sterile 1-L bottles, and then large-volume samples (average of 853 L) were collected using dead-end ultrafiltration (Smith and Hill 2009). Taps were sterilized with flame prior to sample collection, and new tubing and adapters were used for each sample. For large-volume samples, microbes were eluted from ultrafilters following Smith and Hill (2009). Samples were further concentrated by polyethylene glycol flocculation as described in Borchardt et al. (2021), and sample concentrate was stored at -80 °C. For 1-L samples, 10.1 mL of 2.5 M $MgCl_2$ were added to the sample prior to filtration through a 0.45-micron mixed cellulose ester filter (Haramoto et al. 2012, Katayama et al. 2002), and filters were eluted using 5 mL of solution containing $Na_4P_2O_7 \cdot 10H_2O$, $C_{10}H_{13}N_2O_8Na_3 \cdot 3H_2O$, and Tween 80. Samples were stored at -80 °C following addition of beef extract.

Sample concentrate from large-volume and 1-L samples were processed and analyzed identically. Nucleic acids were extracted from sample concentrate using a QIAcube® (Qiagen, Valencia, CA) as described by Borchardt et al. (2021), and virus RNA was reverse-transcribed using random hexamers as described by Borchardt et al. (2021). Samples were analyzed by quantitative polymerase chain reaction (qPCR) in duplicate using a LightCycler® 480 (Roche Diagnostics) for the assays reported in Borchardt et al. (2021). In addition, samples were analyzed for hepatitis E virus (Jothikumar et al. 2006; Garson et al. 2012), porcine adenovirus (Hundesa et el. 2009), porcine epidemic diarrhea virus (Miller et al. 2016), Pig-1-*Bacteroidales* (Mieszkin et al. 2009), and Pig-2-*Bacteroidales* (Mieszkin et al. 2009).

Negative controls for secondary concentration, extraction, reverse transcription, and qPCR were analyzed with samples and must exhibit no cycle of quantification value. Modified live virus vaccines were used for DNA (bovine herpes virus) and RNA (bovine respiratory syncytial virus**)** extraction positive controls, with the latter serving as the reverse transcription positive control, and were evaluated qualitatively. Ultramers® or Minigenes (Integrated DNA Technology) were used as qPCR positive controls for each target and must yield C_q values within 1 cycle of the expected value. qPCR and reverse transcription-qPCR inhibition were evaluated as described in Borchardt et al. (2021); inhibited samples were diluted with AE buffer (Qiagen) prior to qPCR.

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Appendix 4: Statistical methods for risk factor assessment (Objectives 4 and 5)

Univariable modeling to identify associations between well contamination and risk factors was completed as described in Borchardt et al. (2021), available at https://ehp.niehs.nih.gov/doi/full/10.1289/EHP7813. Risk factors were evaluated for their association with the probability of contaminant detection using log-binomial regression and the contaminant concentration using gamma regression with a natural log link function. Significant risk factors were identified based on three criteria: 1) strength of association, 2) plausibility, and 3) consistency. The model p-value was used for criterion 1, where lower p-values indicate stronger associations. For an association to be plausible it must be biologically or physically possible (e.g., it's plausible that increasing the number of nearby septic systems increases well contamination, but it is not plausible that decreasing the number of nearby septic systems increases contamination). Consistency refers to risk factors of the same type but different levels having similar trends (e.g., the number of septic systems within 750, 1500, and 3000 feet of a well are different levels of the same risk factor and should exhibit similar trends). When multiple risk factors of the same type were significant, the one with the strongest association was reported.

Interpretation of the statistical results requires three elements. First, the p-value, which ranges from 0 to 1, describes the likelihood that the association is real, with lower values indicating higher likelihood. For example, a p-value of 0.10 indicates a 10% chance that the observed association was random. Only risk factors that were associated with contamination at a reasonable level ($p < 0.15$) are included in Tables 5 – 18. Second, the trend describes the association between the risk factor and contamination: a positive trend indicates that contamination increases as the value of the risk factor increases, while a negative trend indicates that contamination increases as the value of the risk factor decreases. Third, Tables 10 – 12 and Tables 16 – 18 report the probability of contamination at the minimum and maximum observed values of each risk factor, which illustrates the range of estimated contamination probabilities associated with the risk factor.

All risk factors identified as significant using univariable modeling have a plausible association with contamination. Multivariable analyses can evaluate each important risk factor in the presence of the other important risk factors (i.e., adjusting for the effect of other risk factors), which may refine our understanding of the univariable associations.

Multivariable statistics: the next step

Many factors were related to private well contamination. Factors were identified using a standard approach that examines one factor at a time.

More sophisticated approaches, called "**multivariable statistics**," are useful for examining each factor while accounting for the others. **Multivariable statistics** can identify inter-relationships among factors and their relative importance.

Factors will be further examined using **multivariable statistics** to provide additional insights that go beyond the 5 study objectives covered in this report. Findings will be reported in a scientific journal.

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Appendix 5: Participation and results by county

Table A2. Random selection and participation in the November 2018 and April 2019 synoptic sampling events for total coliforms, *E. coli*, and nitrate.

County	November 2018			April 2019		
	Wells randomly selected	Well samples received	Participation rate (%)	Wells randomly selected	Well samples received	Participation rate (%)
Grant	609	122	20	1051	250	24
Iowa	370	117	32	591	187	32
Lafayette	271	62	23	441	102	23
Total	1250	301	24	2083	539	26

[a]The difference between the number of wells randomly selected and samples received includes 1) well owners that were invited to participate but did not respond and 2) those that responded and received a sampling kit but did not submit a sample.

Table A3. Percentage of private well samples positive for total coliforms and *E. coli* and with high nitrate by county.

County	November 2018					April 2019				
		Percentage of wells positive					Percentage of wells positive			
	No. Wells	Total coliform	*E. coli*	NO_3^--N > 10 mg/L	Total coliform and/or NO_3^--N > 10 mg/L	No. Wells	Total coliform	*E. coli*	NO_3^--N > 10 mg/L	Total coliform and/or NO_3^--N > 10 mg/L
Grant	122	38	7	12	43	250	14	1	13	25
Iowa	117	26	3	13	33	187	14	1	13	25
Lafayette	62	40	3	27	55	102	23	4	20	35
Total	301	34	4	16	42	539	16	2	15	27

Table A4. Microbial source tracking results identifying fecal sources of contamination in private wells by county.

Fecal source	Fecal marker	Number of positive wells		
		Grant (n = 52)[a]	Iowa (n = 46)	Lafayette (n = 40)
Human wastewater	*Bacteroidales*-like HumM2	5	5	2
	Cryptosporidium hominis	5	3	0
	Human adenovirus groups A-F	1	1	0
	Human *Bacteroides* (HF183/R287)	20	20	16
	Human enterovirus	0	1	0
	Human polyomavirus	0	0	0
	Norovirus genogroup I	0	0	0
	Any human wastewater marker[b]	25	23	16
Bovine/ruminant manure	Bacteroidales-like Cow M2	0	0	0
	Bacteroidales-like Cow M3	0	0	0
	Bovine adenovirus	1	0	0
	Bovine enterovirus	0	0	1
	Bovine polyomavirus	0	0	1
	Ruminant *Bacteroides*	11	9	12
	Any bovine or ruminant manure marker[b]	11	9	13
Porcine manure	Pig-1-*Bacteroidales*	3	2	2
	Pig-2-*Bacteroidales*	1	2	5
	Porcine epidemic diarrhea virus	0	0	0
	Porcine adenovirus	0	0	0
	Any porcine manure marker[b]	4	3	6

[a]"n=" refers to the number of wells tested: 52 in Grant County, 46 in Iowa County, and 40 in Lafayette County.

[b]The number of positive wells for any human wastewater marker and any livestock (bovine and porcine) manure marker does not equal the sum of individual fecal markers because some wells were positive for multiple fecal markers.

Table A5. Pathogen occurrence in private wells by county.

Pathogen	Number of positive wells		
	Grant (n = 52)[a]	Iowa (n = 46)	Lafayette (n = 40)
Campylobacter jejuni	1	2	0
Cryptosporidium hominis	5	3	0
Cryptosporidium parvum	5	2	1
Cryptosporidium spp.	12	8	9
Giardia duodenalis assemblage B	1	0	0
Hepatitis E virus	0	0	0
Human adenovirus groups A-F	1	1	0
Human enterovirus	0	1	0
Human polyomavirus	0	0	0
Norovirus genogroup I	0	0	0
Norovirus genogroup II	0	1	1
Pathogenic *E. coli*	0	0	0
Rotavirus group A	4	3	2
Rotavirus group C	1	0	1
Salmonella	3	4	6
Shiga toxin 1-producing bacteria	0	0	1
Shiga toxin 2-producing bacteria	0	0	0
Any pathogen[b]	26	19	21

Note: While tests identified pathogen-specific genes, pathogen names are listed for clarity of presentation. Two genes were tested for rotavirus group A and *Salmonella*.

[a]"n=" refers to the number of wells tested: 52 in Grant County, 46 in Iowa County, and 40 in Lafayette County.

[b]The number of positive wells for "any pathogen" does not equal the sum of individual pathogens because some wells were positive for multiple pathogens

Appendix 6: Computations for volume of septic system effluent and livestock manure

County records indicate that there were approximately 15,930 septic systems in the three-county region that serve an average of 2.45 people each (U.S. Census Bureau). Assuming an average daily per capita water usage (including bathing, laundry, etc.) of 48 gallons (Maupin et al. 2016), septic systems in the study area release 2.6 billion liters (687 million gal) of effluent per year. According to county records, the majority (90%) of private septic systems in the study area are designed to release effluent to the subsurface (i.e., to a drainfield or mound), whereas few (2%) are holding tanks from which wastewater is pumped and subsequently treated. System type was unknown for 8%.

The primary livestock in the study area include cattle, pigs, and poultry. All livestock counts are based on the USDA-NASS 2017 Census of Agriculture for the study area (NASS 2019). There are 369,128 cattle (including milk cows, beef cows, and calves) that excrete an average of 66.3 kg of manure (fecal plus urine) per day (Nennich et al. 2005), totaling 8.9 billion kg per year. When converted to a volume for comparison (based on a density of 1.0 kg/L; University of Wisconsin-Extension 2015), this equals 8.9 billion L per year (2.4 billion gal). There are 77,600 hogs and pigs that excrete an average of 5.1 kg of manure (feces plus urine) per day (ASAE 2003). When converted to volume (based on a density of 0.99 kg/L; ASAE 2003), this equals 146 million L per year (39 million gal).

Animal mass, excrement mass, and excrement density are based on the Manure Production and Characteristics Standards from the American Society of Agricultural Engineers (ASAE 2003) for the computation of poultry manure. There are 248 turkeys in the study area that excrete 0.32 kg per day (assuming an average animal mass of 6.8 kg), which equals 29,000 L per year (based on a density of 1.0 kg/L). There are 164,634 broilers that excrete 0.077 kg per day (assuming an average animal mass of 0.9 kg), which equals 4.6 million L per year (based on a density of 1.0 kg/L). There are 440,964 pullets and layers that excrete 0.12 kg per day (assuming an average animal mass of 1.8 kg), which equals 19 million L per year (based on a density of 0.97 kg/L). The sum of poultry manure is 24 million L per year (6.3 million gal). Poultry are potential hosts of the zoonotic pathogens included in this study, but tests for poultry-specific fecal material were not included. The volume of poultry manure produced in the study area is included for reference, and it is six times less than the volume of pig manure and over 100 times less than that of cattle manure and septic system effluent.

There are 88,600 deer in the study area (WDNR 2018) that each excrete 0.26 kg/day (McCullough 1982), totaling 8.4 million kg/year (19 million lbs).

The manure computations used average values for excrement, though specific excrement mass varies by animal size, type, and age (e.g., heifer versus lactating cow). Likewise, excrement values were not available for pullets, so the value for layers was used. The computations describe the amount of manure produced in the three-county area but do not account for manure that is produced elsewhere and applied in the study area or for manure that is produced in the study area and applied elsewhere.

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Appendix 7: Risk factors and data sources

Table A6. Risk factors for private well contamination included in statistical modeling (Objectives 4 and 5)

Category	Risk factor
Geology	Aquitard count
	Bedrock depth
	Open interval geology
	Topmost bedrock
Well characteristics	Casing depth
	Groundwater depth at construction
	Casing length below water level
	Casing length into bedrock
	Open interval length
	Specific capacity
	Well age
	Well depth
Well siting	Slope at well
	Slope, mean and maximum within 750 ft, 1500 ft, and 3000 ft
	Soil hydrologic group
	Surficial sediment type
	Well elevation
Groundwater and rainfall	Groundwater depth, antecedent (2, 7, 14, 21 day), median and minimum
	Groundwater recharge, antecedent (2, 7, 14, 21 day), cumulative
	Rainfall, antecedent (2, 7, 14, 21 day), cumulative
Agriculture	Cultivated land: area within 750 ft, 1500 ft, and 3000 ft
	Cultivated land: distance to nearest
	Livestock farms excluding hobby farms: count within 750 ft, 1500 ft, and 3000 ft
	Livestock farms excluding hobby farms: distance to nearest
	Livestock farms: count within 750 ft, 1500 ft, and 3000 ft
	Livestock farms: distance to nearest
Septic systems	Septic systems: count within 750 ft, 1500 ft, and 3000 ft
	Septic systems: distance to nearest
	Drainfield septic systems: count within 750 ft, 1500 ft, and 3000 ft
	Drainfield septic systems: distance to nearest
Land-applied waste	Septage-applied fields: distance to nearest
	Septage-applied fields: count within 750 ft, 1500 ft, and 3000 ft
	Municipal sludge-applied fields: distance to nearest
	Municipal sludge-applied fields: count within 750 ft, 1500 ft, and 3000 ft
	Septage- or municipal sludge-applied fields: distance to nearest
	Septage- or municipal sludge-applied fields: count within 750 ft, 1500 ft, and 3000 ft

Geology. Topmost bedrock and aquitard count (number of aquitards at the well location) were identified using existing geologic maps and well construction reports. Bedrock depth and open interval geology were determined for each well using the well construction report and existing geologic maps. Open interval geology refers to the portion of the well that is not cased, and it is an indication of which aquifer the well draws water from. There are two major aquifers in the study area, an upper and lower aquifer; some wells also draw from sand/gravel aquifers. Topmost bedrock refers to the topmost geologic group where the well is located (regardless of whether the well draws water from that unit).

Well characteristics. Well characteristics were abstracted from well construction reports, which were obtained for 74% of the study wells. Open interval length, length of casing into bedrock, length of casing into static water level, and specific capacity were derived from data in well construction reports. Wells without construction reports were not included in risk factor tests for these factors.

Well siting. Elevation at the land surface was from the 10-meter digital elevation model obtained from Wisconsin DNR (https://data-wi-dnr.opendata.arcgis.com/search?q=elevation). Slope of the land surface was calculated from the 10-meter digital elevation model and identified for each well using ESRI ArcMap (ESRI 2011); slope was also characterized as the average and maximum within 750 feet, 1500 feet, and 3000 feet of each well. Soil hydrologic group was from the USDA Natural Resources Conservation Service's Soil Survey (ssurgo), obtained from the USDA Geospatial Data Gateway (https://datagateway.nrcs.usda.gov/). Soil hydrologic group is an assessment of soil drainage that describes the tendency for water to infiltrate or run off (NRCS 1996). Surficial sediment (coarse or fine) was obtained from well construction reports.

Groundwater and rainfall. Quantitative precipitation estimates (QPE) were provided by the National Oceanic and Atmospheric Administration for each well (QPE data are generated on a 2 km x 2 km grid). Snowfall was excluded from precipitation totals by cross-referencing snowfall data from a local weather station (National Climatic Data Center). Groundwater levels were from three groundwater monitoring wells in the study area located in differing hydrogeologic settings and are open to different geologic units: one was open to the lower aquifer, one was open to the upper aquifer (also referred to as the Galena-Platteville aquifer) without Maquoketa Shale, and one was open to the upper aquifer and was overlain by the Maquoketa Shale. Groundwater recharge was determined using the Water Table Fluctuation method (Healy and Cook 2002).

Agriculture. The distance from each well to the edge of the nearest cultivated field was determined. The area of cultivated land within 750, 1500, and 3000 feet of each well was also determined; these three radii were selected *a priori* based on previous work (Borchardt et al. 2003; Borchardt et al. 2021). Cultivated land was from USDA's 2019 National Cultivated Layer (obtained from USDA NASS at www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php), which bases the designation of cultivated land on crop data from 2015 to 2019.

Farm locations were identified from aerial imagery based on evidence of livestock as described in Muldoon et al. (2021). A subset of farms excluded farms with evidence of lesser livestock presence and was referred to as "Livestock farms excluding hobby farms." Livestock farm point locations were based on the primary farm structures. Distance from each well to the nearest livestock farm was determined. ESRI ArcMap (ESRI 2011) was used for spatial analyses.

Septic systems. Septic system locations for Lafayette County were from an existing county GIS layer. Septic system GIS layers were developed for Grant and Iowa Counties using county records as described in Muldoon et al. (2021). A subset of septic systems with drainfields was created using data from county records. The count of septic systems within 750, 1500, and 3000 feet of each well was determined. The distance to the nearest neighbor's septic system was determined (excluded septic systems on the same parcel as the well). ESRI ArcMap was used for spatial analyses.

Land-applied waste. Point locations of permitted waste application sites were provided by Wisconsin DNR. Points were located near the site center. Only sites with permits for the application of septage and municipal sludge were included. The distance to the nearest application site was determined for each well using ESRI ArcMap.

Table A7. Descriptive statistics of risk factors for wells sampled in the November synoptic event.

Category	Risk factor	Units	N[a]	Mean	Min.	Lower Quartile	Median	Upper Quartile	Max.
Geology	Aquitard count	Count	230	1	0	0	1	2	2
	Bedrock depth	ft	301	16	0	5	9	15	151
	Open interval geology	NA	228	NA	NA	NA	NA	NA	NA
	Topmost bedrock	NA	301	NA	NA	NA	NA	NA	NA
Well characteristics	Casing depth	ft	224	112	15	47	84	147	434
	Groundwater depth at construction	ft	225	127	2	65	120	170	460
	Casing length below water level	ft	224	-14	-300	-50	-2	30	140
	Casing length into bedrock	ft	216	96	-2	36	63	141	370
	Open interval length	ft	224	108	0	57	92	151	350
	Specific capacity	gpm/ft	194	2	0.1	0.4	1	3	14
	Well age	Years	226	30	0.2	16	28	42	71
	Well depth	ft	226	219	54	145	208	275	548
Well siting	Slope at well	%	301	28	0	14	25	40	129
	Slope, mean within 750 ft	%	301	35	1	25	34	44	93
	Slope, mean within 1500 ft	%	301	35	2	27	35	45	96
	Slope, mean within 3000 ft	%	301	36	2	27	36	46	74
	Slope, maximum within 750 ft	%	301	99	6	70	98	145	486
	Slope, maximum within 1500 ft	%	301	129	7	95	134	191	543
	Slope, maximum within 3000 ft	%	301	164	35	124	172	242	804
	Soil hydrologic group	NA	301	NA	NA	NA	NA	NA	NA
	Surficial sediment type	NA	301	NA	NA	NA	NA	NA	NA
	Well elevation	ft above sea level	301	986	631	899	998	1085	1317
Agriculture	Cultivated land: area within 750 ft	Ac	301	13	0	4	13	20	37
	Cultivated land: area within 1500 ft	Ac	301	63	0	34	59	90	153
	Cultivated land: area within 3000 ft	Ac	301	262	12	165	238	348	613
	Cultivated land: distance to nearest	ft	301	141	0	41	92	175	2050
	Livestock farms excluding hobby farms: count within 750 ft	Count	301	0.2	0	0	0	0	2
	Livestock farms excluding hobby farms: count within 1500 ft	Count	301	0.5	0	0	0	1	6
	Livestock farms excluding hobby farms: count within 3000 ft	Count	301	2	0	1	2	3	8
	Livestock farms excluding hobby farms: distance to nearest	ft	301	3997	26	1100	2108	4005	26015
	Livestock farms: count within 750 ft	Count	301	0.3	0	0	0	1	2
	Livestock farms: count within 1500 ft	Count	301	0.6	0	0	0	1	6
	Livestock farms: count within 3000 ft	Count	301	2	0	1	2	3	8
	Livestock farms: distance to nearest	ft	301	1817	26	687	1594	2596	8422

Septic systems	Septic systems: count within 750 ft	Count	301	3	1	1	2	3	24
	Septic systems: count within 1500 ft	Count	301	6	1	2	3	7	63
	Septic systems: count within 3000 ft	Count	301	14	1	5	9	15	108
	Septic systems: distance to nearest	ft	301	799	46	275	613	1174	2968
	Drainfield septic systems: count within 750 ft	Count	301	3	0	1	2	3	24
	Drainfield septic systems: count within 1500 ft	Count	301	5	0	2	3	6	61
	Drainfield septic systems: count within 3000 ft	Count	301	13	0	5	8	13	105
	Drainfield septic systems: distance to nearest	ft	301	844	46	287	657	1228	3777
Land-applied waste	Septage-applied fields: distance to nearest	ft	301	29959	711	17215	25129	39181	100547
	Septage-applied fields: count within 750 ft	Count	301	0.007	0	0	0	0	1
	Septage-applied fields: count within 1500 ft	Count	301	0.01	0	0	0	0	2
	Septage-applied fields: count within 3000 ft	Count	301	0.03	0	0	0	0	4
	Municipal sludge-applied fields: distance to nearest	ft	301	15421	441	7507	13270	20283	63052
	Municipal sludge-applied fields: count within 750 ft	Count	301	0.01	0	0	0	0	1
	Municipal sludge-applied fields: count within 1500 ft	Count	301	0.04	0	0	0	0	2
	Municipal sludge-applied fields: count within 3000 ft	Count	301	0.2	0	0	0	0	7
	Septage- or municipal sludge-applied fields: distance to nearest	ft	301	12525	441	6417	11125	17271	45451
	Septage- or municipal sludge-applied fields: count within 750 ft	Count	301	0.02	0	0	0	0	1
	Septage- or municipal sludge-applied fields: count within 1500 ft	Count	301	0.05	0	0	0	0	2
	Septage- or municipal sludge-applied fields: count within 3000 ft	Count	301	0.2	0	0	0	0	7

NA, not applicable for categorical risk factors; Min., minimum; Max., maximum; ft, feet; gpm, gallons per minute; ac, acres
[a]N is the number of wells for which the risk factor data were available

Table A8. Descriptive statistics of risk factors for wells sampled in the April synoptic event.

Category	Risk factor	Units	N[a]	Mean	Min.	Lower Quartile	Median	Upper Quartile	Max.
Geology	Aquitard count	Count	392	1	0	0	1	2	3
	Bedrock depth	ft	539	17	0	5	10	16	166
	Open interval geology	NA	392	NA	NA	NA	NA	NA	NA
	Topmost bedrock	NA	539	NA	NA	NA	NA	NA	NA
Well characteristics	Casing depth	ft	387	117	20	48	89	168	380
	Groundwater depth at construction	ft	389	129	0	65	120	186	410
	Casing length below water level	ft	387	-11	-334	-47	0	35	215
	Casing length into bedrock	ft	376	105	-6	38	77	159	368
	Open interval length	ft	387	109	2	57	94	142	462
	Specific capacity	gpm/ft	349	2	0	0	1	3	15
	Well age	Years	391	29	1	15	24	43	78
	Well depth	ft	389	226	30	151	220	298	560
Well siting	Slope at well	%	539	30	0	14	27	43	109
	Slope, mean within 750 ft	%	539	35	2	25	35	46	108
	Slope, mean within 1500 ft	%	539	35	2	26	35	46	96
	Slope, mean within 3000 ft	%	539	35	1	26	35	44	73
	Slope, maximum within 750 ft	%	539	103	6	71	104	149	691
	Slope, maximum within 1500 ft	%	539	130	6	92	136	198	797
	Slope, maximum within 3000 ft	%	539	162	6	126	178	242	804
	Soil hydrologic group	NA	539	NA	NA	NA	NA	NA	NA
	Surficial sediment type	NA	539	NA	NA	NA	NA	NA	NA
	Well elevation	ft above sea level	539	978	618	894	982	1068	1278
Agriculture	Cultivated land: area within 750 ft	Ac	539	13	0	5	12	20	38
	Cultivated land: area within 1500 ft	Ac	539	62	0.4	30	58	88	155
	Cultivated land: area within 3000 ft	Ac	539	265	6	145	242	368	595
	Cultivated land: distance to nearest	ft	539	153	0	40	110	195	1233
	Livestock farms excluding hobby farms: count within 750 ft	Count	539	0.2	0	0	0	0	2
	Livestock farms excluding hobby farms: count within 1500 ft	Count	539	0.5	0	0	0	1	4
	Livestock farms excluding hobby farms: count within 3000 ft	Count	539	1	0	0	1	2	7
	Livestock farms excluding hobby farms: distance to nearest	ft	539	3743	35	1023	2077	3952	23191
	Livestock farms: count within 750 ft	Count	539	0.3	0	0	0	1	2
	Livestock farms: count within 1500 ft	Count	539	0.6	0	0	0	1	4
	Livestock farms: count within 3000 ft	Count	539	2	0	1	2	3	8
	Livestock farms: distance to nearest	ft	539	1783	35	680	1528	2484	8862
	Septic systems: count within 750 ft	Count	539	3	1	1	2	3	37

Septic systems	Septic systems: count within 1500 ft	Count	539	6	1	2	3	6	71
	Septic systems: count within 3000 ft	Count	539	14	1	5	8	14	131
	Septic systems: distance to nearest	ft	539	837	53	296	656	1186	3661
	Drainfield septic systems: count within 750 ft	Count	539	3	0	1	1	3	28
	Drainfield septic systems: count within 1500 ft	Count	539	5	0	2	3	6	69
	Drainfield septic systems: count within 3000 ft	Count	539	12	0	5	8	13	129
	Drainfield septic systems: distance to nearest	ft	539	881	53	305	675	1284	3883
Land-applied waste	Septage-applied fields: distance to nearest	ft	539	32589	1531	17658	28152	44782	111143
	Septage-applied fields: count within 750 ft	Count	539	0	0	0	0	0	0
	Septage-applied fields: count within 1500 ft	Count	539	0	0	0	0	0	0
	Septage-applied fields: count within 3000 ft	Count	539	0.007	0	0	0	0	1
	Municipal sludge-applied fields: distance to nearest	ft	539	14746	308	6760	12202	20489	58094
	Municipal sludge-applied fields: count within 750 ft	Count	539	0.03	0	0	0	0	12
	Municipal sludge-applied fields: count within 1500 ft	Count	539	0.08	0	0	0	0	12
	Municipal sludge-applied fields: count within 3000 ft	Count	539	0.2	0	0	0	0	12
	Septage- or municipal sludge-applied fields: distance to nearest	ft	539	11960	308	6102	10775	16625	46316
	Septage- or municipal sludge-applied fields: count within 750 ft	Count	539	0.03	0	0	0	0	12
	Septage- or municipal sludge-applied fields: count within 1500 ft	Count	539	0.08	0	0	0	0	12
	Septage- or municipal sludge-applied fields: count within 3000 ft	Count	539	0.2	0	0	0	0	12

NA, not applicable for categorical risk factors; Min., minimum; Max., maximum; ft, feet; gpm, gallons per minute; ac, acres
[a]N is the number of wells for which the risk factor data were available.

Table A9. Descriptive statistics of risk factors for wells sampled for human wastewater and livestock manure.

Category	Risk factor	Units	N[a]	Mean	Min.	Lower Quartile	Median	Upper Quartile	Max.
Geology	Aquitard count	Count	96	1	0	0	1	2	2
	Bedrock depth	ft	138	14	1	5	9	15	150
	Open interval geology	NA	95	NA	NA	NA	NA	NA	NA
	Topmost geology	NA	138	NA	NA	NA	NA	NA	NA
Well characteristics	Casing depth	ft	94	86	19	42	62	103	375
	Groundwater depth at construction	ft	95	110	3	55	89	150	402
	Casing length below water level	ft	93	-24	-334	-49	-7	21	140
	Casing length into bedrock	ft	89	70	1	34	46	81	370
	Open interval length	ft	94	109	4	51	86	154	462
	Specific capacity	gpm/ft	70	2	0	1	1	3	15
	Well age	Years	95	37	4	22	36	52	74
	Well depth	ft	96	194	30	125	180	242	530
Well siting	Slope at well	%	138	26	0	12	25	38	93
	Slope, mean within 750 ft	%	138	32	3	22	30	42	93
	Slope, mean within 1500 ft	%	138	32	4	22	32	42	96
	Slope, mean within 3000 ft	%	138	33	3	24	32	41	74
	Slope, maximum within 750 ft	%	138	89	14	61	85	128	315
	Slope, maximum within 1500 ft	%	138	115	32	81	121	162	385
	Slope, maximum within 3000 ft	%	138	147	52	110	154	230	596
	Soil hydrologic group	NA	138	NA	NA	NA	NA	NA	NA
	Surficial sediment	NA	138	NA	NA	NA	NA	NA	NA
	Well elevation	ft above sea level	138	995	654	933	997	1074	1251
Groundwater and rainfall	Groundwater depth , antecedent 2 day, median	ft	138	35.3	8.7	10.3	49.1	54.5	55.8
	Groundwater depth , antecedent 7 day, median	ft	138	35.1	8.6	10.3	48.8	54.2	56.0
	Groundwater depth , antecedent 14 day, median	ft	138	34.8	8.4	10.4	47.7	54.0	55.9
	Groundwater depth , antecedent 21 day, median	ft	138	34.4	8.1	10.4	45.8	53.2	55.8
	Groundwater depth , antecedent 2 day, minimum	ft	138	34.9	8.6	10.1	48.9	54.2	55.6
	Groundwater depth , antecedent 7 day, minimum	ft	138	34.4	8.3	10.1	47.6	53.6	55.6
	Groundwater depth , antecedent 14 day, minimum	ft	138	33.3	7.5	9.9	43.7	52.2	55.6
	Groundwater depth , antecedent 21 day, minimum	ft	138	32.3	7.1	9.2	39.6	50.8	55.2
	Groundwater recharge, antecedent 2 day, cumulative	ft	138	0.015	0.000	0.009	0.015	0.024	0.031
	Groundwater recharge, antecedent 7 day, cumulative	ft	138	0.031	0.000	0.016	0.033	0.045	0.068
	Groundwater recharge, antecedent 14 day, cumulative	ft	138	0.273	0.002	0.025	0.063	0.119	2.556
	Groundwater recharge, antecedent 21 day, cumulative	ft	138	0.831	0.011	0.039	0.098	0.165	7.046
	Rainfall, antecedent 2 day, cumulative	in	138	0.46	0.00	0.05	0.29	0.55	1.99

	Rainfall, antecedent 7 day, cumulative	in	138	0.72	0.00	0.08	0.48	1.15	2.16
	Rainfall, antecedent 14 day, cumulative	in	138	1.07	0.00	0.08	1.07	1.41	2.81
	Rainfall, antecedent 21 day, cumulative	in	138	2.11	0.39	0.74	1.46	1.78	7.83
Agriculture	Cultivated land: area within 750 ft	Ac	138	16	0	7	16	24	38
	Cultivated land: area within 1500 ft	Ac	138	75	0	47	79	105	155
	Cultivated land: area within 3000 ft	Ac	138	88	2	48	81	111	553
	Cultivated land: distance to nearest	ft	138	139	0	30	91	170	2049
	Livestock farms excluding hobby farms: count within 750 ft	Count	138	0.3	0	0	0	1	2
	Livestock farms excluding hobby farms: count within 1500 ft	Count	138	0.5	0	0	0	1	3
	Livestock farms excluding hobby farms: count within 3000 ft	Count	138	2	0	0	1	2	6
	Livestock farms excluding hobby farms: distance to nearest	ft	138	3164	35	709	1776	3289	21884
	Livestock farms: count within 750 ft	Count	138	0.3	0	0	0	1	2
	Livestock farms: count within 1500 ft	Count	138	0.6	0	0	0	1	3
	Livestock farms: count within 3000 ft	Count	138	2	0	1	2	3	6
	Livestock farms: distance to nearest	ft	138	1694	35	629	1570	2445	5666
Septic systems	Septic systems: count within 750 ft	Count	138	2	1	1	1	2	18
	Septic systems: count within 1500 ft	Count	138	4	1	1	2	4	41
	Septic systems: count within 3000 ft	Count	138	10	1	5	7	12	105
	Septic systems: distance to nearest	ft	138	993	89	391	821	1443	3661
	Drainfield septic systems: count within 750 ft	Count	138	2	0	1	1	2	18
	Drainfield septic systems: count within 1500 ft	Count	138	4	0	1	2	4	36
	Drainfield septic systems: count within 3000 ft	Count	138	9	0	4	7	11	85
	Drainfield septic systems: distance to nearest	ft	138	1064	89	400	870	1574	3662
Land-applied waste	Septage-applied fields: distance to nearest	ft	138	30658	739	17219	26932	39795	101914
	Septage-applied fields: count within 750 ft	Count	138	0.007	0	0	0	0	1
	Septage-applied fields: count within 1500 ft	Count	138	0.007	0	0	0	0	1
	Septage-applied fields: count within 3000 ft	Count	138	0.03	0	0	0	0	3
	Municipal sludge-applied fields: distance to nearest	ft	138	13872	679	6949	10979	19612	63052
	Municipal sludge-applied fields: count within 750 ft	Count	138	0.007	0	0	0	0	1
	Municipal sludge-applied fields: count within 1500 ft	Count	138	0.01	0	0	0	0	1
	Municipal sludge-applied fields: count within 3000 ft	Count	138	0.1	0	0	0	0	3
	Septage- or municipal sludge-applied fields: distance to nearest	ft	138	11301	679	5436	9386	16236	45451
	Septage- or municipal sludge-applied fields: count within 750 ft	Count	138	0.01	0	0	0	0	1
	Septage- or municipal sludge-applied fields: count within 1500 ft	Count	138	0.02	0	0	0	0	1
	Septage- or municipal sludge-applied fields: count within 3000 ft	Count	138	0.1	0	0	0	0	3

NA, not applicable for categorical risk factors; Min., minimum; Max., maximum; ft, feet; gpm, gallons per minute; ac, acres
[a]N is the number of wells for which the risk factor data were available

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