RELATION BETWEEN SELECTED WELL-CONSTRUCTION CHARACTERISTICS AND OCCURRENCE OF BACTERIA IN PRIVATE HOUSEHOLD-SUPPLY WELLS, SOUTH-CENTRAL AND SOUTHEASTERN PENNSYLVANIA

by Tammy M. Zimmerman, Michele L. Zimmerman, and Bruce D. Lindsey

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 01-4206

In cooperation with

THE PENNSYLVANIA DEPARTMENT OF ENVIRONMENTAL PROTECTION
BUREAU OF WATER SUPPLY AND WASTEWATER MANAGEMENT

New Cumberland, Pennsylvania
2001

U.S. DEPARTMENT OF THE INTERIOR

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Multiply	By	To obtain
	Length	
inch	25.4	millimeter
foot	0.3048	meter
	Volume	
gallon	3.785	liter
	Temperature	
degree Fahrenheit (°F)	$C = 5/9 \times (°F - 32)$	degree Celsius (°C)

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ABSTRACT

Total coliform and *Escherichia coli (E. coli)* bacteria were analyzed in ground water sampled from 78 private household-supply wells as part of a study by the U.S. Geological Survey in cooperation with the Pennsylvania Department of Environmental Protection to evaluate the relation between well-construction characteristics and the occurrence of bacteria in ground water. Sampling was done in eight counties in south-central and southeastern Pennsylvania from September 2000 to March 2001. All samples were collected from wells in close proximity to agricultural land-use areas.

Total coliform bacteria were found in water from 62 percent (48 of 78) of the wells, and bacteria were just as likely to be found in sanitary wells (grouted/loose-fitting well cap or grouted/sanitary sealed well cap) as in nonsanitary wells (non-grouted/loose-fitting well cap). The areas underlain by carbonate bedrock had the highest percentages of total coliform detected (about 75 percent). Nearly half of the samples collected in the areas underlain by noncarbonate bedrock also were found to have total coliform present. *E. coli* bacteria were found in water from 10 percent of the wells. Seventeen percent of the samples that were positive for total coliform also were positive for *E. coli*. The presence of *E. coli* bacteria was more likely in water from nonsanitary wells. Additionally, the presence of *E. coli* bacteria was more likely in ground water from wells underlain by carbonate bedrock. A further breakdown of the data into four groups on the basis of sanitary construction and bedrock type indicated the presence of *E. coli* was more likely in water from nonsanitary wells in areas underlain by carbonate bedrock.

Statistical analysis of other well-construction characteristics that might relate to occurrence of bacteria showed that the presence of total coliform bacteria was related to the depth to water-bearing zone in both sanitary and nonsanitary wells in areas underlain by carbonate bedrock. Relations also are present between the presence of total coliform bacteria and casing length in nonsanitary wells in areas underlain by noncarbonate bedrock. Bacteria were found in wells both with and without insects observed on the underside of the well cap. Because of the small number of wells sampled that had sanitary sealed caps, it is uncertain whether installation of sanitary sealed well caps would reduce the incidence of bacteria in ground water from wells or if the presence of bacteria is because of a combination of well-construction characteristics or aquifer-wide contamination of limited or broad areal extent.

INTRODUCTION

A common belief is that untreated ground water generally is safe for consumptive use. This belief is a concern given that nationally, 24 million people rely on private or individual water systems as their source of drinking water supply (Barwick and others, 2000). According to Yates and Yates (1993), the consumption of contaminated ground water has been responsible for about one-half of all reported outbreaks of waterborne diseases in the United States since the early 1900’s. Since 1971, the U.S. Environmental Protection Agency (EPA) and the Center for Disease Control and Prevention jointly have maintained a surveillance system for collecting and periodically reporting data that pertain to waterborne-disease outbreaks (WBDO’s). The most recent report was from WBDO’s in the United States in 1997 and 1998 (Barwick and others, 2000). A total of 13 states reported 17 outbreaks associated with drinking water, causing approximately 2,083 individuals to become ill. Fifteen of these outbreaks (88 percent) were linked to ground-water sources. Four outbreaks (24 percent) were in private or individual water systems with no form of water treatment. The etiologic agents associated with the outbreaks from ground-water sources included *Giardia*, *Cryptosporidium*, and the O157:H7 strain of *Escherichia coli (E. coli)*. Because the recognition, investigation, and reporting of WBDO’s is voluntary on behalf of state, territorial, and local health departments, the data probably are an underestimate of the actual incidence of such outbreaks (Barwick and others, 2000).

Pennsylvania has a large rural population that depends on ground water from private wells as a daily source of drinking water and source of water for livestock. Private water-supply information from the U.S Bureau of the Census (1992) shows about 1 million Pennsylvania households rely on ground water from private on-lot wells for daily water supply. Census statistics also show nearly 4 million households rely on ground water from community or public water-supply systems as their daily source of drinking water. Water-supply information for households with private wells in counties associated with the study on which this report is based is shown in table 1.

Even though Pennsylvania has a high dependency on ground water as a source of drinking water supply, only public water-supply systems currently (2001) require the routine monitoring and treatment of their systems for microbiological contaminants. Protection and maintenance of private, household-supply wells is not regulated and is the responsibility of the homeowner (state water-quality regulations for public-supply wells can be used as a guideline). In addition, Pennsylvania currently has no statewide well-construction requirements, and in most parts of the state, drilling and testing of private on-lot wells is done with no regulatory oversight. However, the Pennsylvania Department of Environmental Protection (PaDEP) recommends wells be sited uphill at least 100 feet from potential sources of contamination such as septic leach fields, roads, fuel tanks, and barnyards (Pennsylvania Department of Environmental Protection, 2000). Typically, private on-lot wells are constructed as open holes completed in bedrock with minimal surface casing, little or no annular grout seal, and a loose-fitting well cap.

Bacteria commonly are detected in ground water from private, on-lot wells used for household supply in Pennsylvania (Sharpe and others, 1985; Bickford and others, 1996). It is not known if the bacterial contamination of the water from these household-supply wells is the result of well-construction characteristics that can allow contaminants from the immediate vicinity to enter the well or if bacterial contamination within the aquifer is widespread. Coliform bacteria generally are not disease-causing (pathogenic). However, the presence of coliform bacteria, a common indicator bacteria used to test the sanitary quality of water supplies, indicates that pathogenic organisms may be present. The U.S. Geological Survey (USGS), in cooperation with the PaDEP, conducted a study to evaluate whether or not the water from private household-supply wells constructed with annular grout have lower incidence of bacterial contamination than wells completed without this well-construction characteristic.

Table 1. *U.S. Bureau of the Census (1990) information for the eight counties in the study area, south-central and southeastern Pennsylvania*

County	Number of households	Number of households in county with private wells	Percentage of households in county with private wells
Chester	133,592	49,316	37
Cumberland	73,506	19,587	27
Dauphin	95,123	21,655	23
Lancaster	151,352	50,966	34
Lebanon	42,708	13,034	31
Montgomery	254,596	30,716	12
Perry	14,930	11,112	74
York	128,764	43,441	34
Total	894,571	239,827	

Purpose and Scope

This report describes the relation between selected well-construction characteristics in south-central and southeastern Pennsylvania and the occurrence of bacteria in ground water. Private household-supply wells in predominantly agricultural land-use settings were the focus of the study; results are based on samples collected from September 2000 to March 2001. Water samples were analyzed for concentrations of total coliform and *E. coli* bacteria. The effect of rock type in two geologic settings (areas underlain by carbonate rock and areas underlain by noncarbonate rock) on the occurrence of bacteria in ground water from sanitary and nonsanitary wells also is presented. A sanitary well refers to a well constructed with grout installed along the entire annulus of casing. A nonsanitary well refers to a well constructed with loose dirt or fill around the annulus of casing.

Previous Investigations

Various studies were done on the occurrence of bacteria in ground water from private, household-supply wells. This section will describe studies conducted nationally, regionally, and locally (basin specific) by the USGS and on a statewide scale by the Pennsylvania Department of Agriculture (PDA).

USGS - NATIONAL MONITORING EFFORT

In 1997, the National Water-Quality Assessment (NAWQA) Program selected four basins across the Nation to participate in a microbiological monitoring program for ground water: the Lake Erie-Lake Saint Clair Basin (LERI), the Kanawha-New River Basin (KANA), the Santee Basin and coastal drainage (SANT), and the Upper Colorado Basin (UCOL) (Francy and others, 2000). Ground-water samples were collected and analyzed for microbiological constituents from March to September 1997. Seventy-four of the 141 ground-water supply wells were private, household-supply wells. Overall, total coliform bacteria were found in 20 percent of 130 samples; *E. coli* bacteria were found in less than 1 percent of the 130 samples.

USGS, TENNESSEE DISTRICT

The USGS, Tennessee District, in cooperation with the University of Tennessee Agricultural Extension Service and the Tennessee Farm Bureau, conducted reconnaissance projects regionally in Tennessee in order to establish a better understanding of the ground-water quality in selected areas of the state. A total of 200 private, household-supply wells were sampled in Bedford and Coffee Counties in the south-central region of Tennessee in June and July 1991. Of these, 38 percent had fecal coliform and 64 percent had fecal streptococcus (Roman-Mas and others, 1991). In August 1996, a follow-up study was conducted in Bedford County (Bennett, 1997). Of the 78 private, household-supply wells sampled, 74 percent were positive for fecal coliform and 81 percent were positive for fecal streptococcus.

Another study was done in western Tennessee in the Beaver Creek watershed and other rural areas of Fayette, Haywood, Shelby, and Tipton Counties. This water-quality investigation in the Beaver Creek watershed was done in 1993 to gain an understanding of the characteristics of the watershed. Of the 408 samples, 8 percent had fecal coliform and 30 percent were positive for fecal streptococcus (Williams, 1996).

PENNSYLVANIA DEPARTMENT OF AGRICULTURE

The PDA sampled ground water from wells completed mainly in carbonate rocks in six counties in Pennsylvania and from wells in rocks of Triassic age in parts of seven counties in southeastern Pennsylvania (John Pari, Pennsylvania Department of Agriculture, written commun., 2001). The types of sites visited include household-supply wells, farms, and commercial and public properties. Samples from the selected wells were analyzed for a variety of ground-water-quality constituents including *E. coli* and total coliform bacteria. The bacteriological data for the selected counties is summarized in table 2.

PENNSYLVANIA BASIN-SPECIFIC USGS PROJECTS

Microbiological data were collected as part of the USGS NAWQA Program in two basins partly contained within Pennsylvania. Total coliform and *E. coli* were analyzed as part of the Delaware River Basin NAWQA. Total coliform, fecal coliform, *E. coli*, and fecal streptococcus were analyzed as part of the Lower Susquehanna River Basin NAWQA. Results of microbiological analyses in each of the basins are described below.

USGS, Delaware River Basin NAWQA.—Thirty private, household-supply and observation wells were sampled as part of the NAWQA Program in the Delaware River Basin. Of these 30 wells, 24 are in 6 counties in Pennsylvania (Berks, Carbon, Lehigh, Monroe, Northampton, and Schuylkill). The other six wells are in New Jersey (Sussex and Warren Counties). The wells were sampled to assess the status of ground-water quality in the clastic (mostly sandstone, siltstone, and shale) bedrock of the Valley and Ridge Physiographic Province. The bacteriological data (total coliform and *E. coli*) from 1999 were not summarized because of the unreliable performance of the bacteria media used. EPA-approved media for drinking water was used in 2000, and of the 30 samples collected from domestic and observation wells, total coliform was detected in 20 percent and *E. coli* was detected in 3 percent of the samples (Durlin and Schaffstall, 2001).

Table 2. *Percentages of total coliform and E. coli bacteria detected in ground water from wells sampled by the Pennsylvania Department of Agriculture*

[John Pari, Pennsylvania Department of Agriculture, written commun., 2001]

Study area	Total samples				Samples from private households		
	Number of samples	Number of wells	Percentage total coliform	Percentage *E. coli*	Number of samples	Percentage total coliform	Percentage *E. coli*
Blair County	120	118	84	48	56	86	36
Bedford County	73	73	70	37	11	73	27
Berks County	44	42	57	16	16	32	12
Lebanon County	26	26	50	12	10	40	0
Lehigh County	8	8	25	12	7	12	0
Northampton County	15	15	40	0	9	44	0
Triassic System	44	44	36	9	13	23	0

USGS, Lower Susquehanna River Basin NAWQA.—The Lower Susquehanna River Basin (LSUS) NAWQA Program sampled 146 private household-supply wells from 1993 to 1995. Seventeen counties in Pennsylvania and two counties in Maryland composed the study unit. Approximately 70 percent of the samples were positive for total coliform, 65 percent for fecal streptococcus, and 25 percent for fecal coliform. Samples were not analyzed for *E. coli* during the first year of the project, but *E. coli* was found in water from 30 percent of the 88 wells sampled in 1994 and 1995. Results of the study showed the following: (1) bacteria were more likely in ground water from wells in agricultural areas, (2) bacteria were more likely in ground water from wells in the Valley and Ridge Physiographic Province, (3) *E. coli* concentrations were higher in areas underlain by carbonate bedrock, and (4) weak relations are present between bacteria concentrations and selected well characteristics and selected water-quality constituents (Bickford and others, 1996).

Results of the LSUS NAWQA Program raised questions as to whether the contamination source is site specific (relating to the well-construction methods) or widespread (contamination of an entire aquifer) and provided the impetus for this study. This study was done to focus on well-construction characteristics in Pennsylvania to determine if those differences make wells any more or less susceptible to bacteriological contamination in predominantly agricultural land-use areas.

Description of Study Area

The study area spanned eight counties in south-central and southeastern Pennsylvania: Chester, Cumberland, Dauphin, Montgomery, Lancaster, Lebanon, Perry, and York (fig. 1). Sites were selected for sampling in two geologic settings: areas underlain by limestone and dolomite bedrock (hereafter termed carbonate bedrock) and areas underlain by noncarbonate bedrock. Areas underlain by carbonate bedrock were targeted for sampling in Cumberland, Dauphin, Lebanon, and Perry Counties. Areas underlain by noncarbonate bedrock were targeted for sampling in Montgomery and York Counties. Areas underlain by either carbonate or noncarbonate bedrock were targeted in Chester and Lancaster Counties. All water samples were collected from wells adjacent to agricultural land-use areas. The areas sampled are described in table 3.

Acknowledgments

The authors thank Stuart Reese of the PaDEP, who provided assistance in developing the project and providing input to USGS personnel as the project was being implemented. The authors gratefully acknowledge the cooperation of the homeowners who allowed access to their private wells for water sampling. The authors also thank Michael Bradley and Douglas Moyer of the USGS and Stuart Reese of the PaDEP for their technical review of this manuscript. A special thanks is extended to Ralph Defazio of the Chester County Health Department, Rachel DeMarzio of the Montgomery County Health Department, and Dave Wetzel of Eichelberger’s Drilling Company for their help in locating potential well sites for this study.

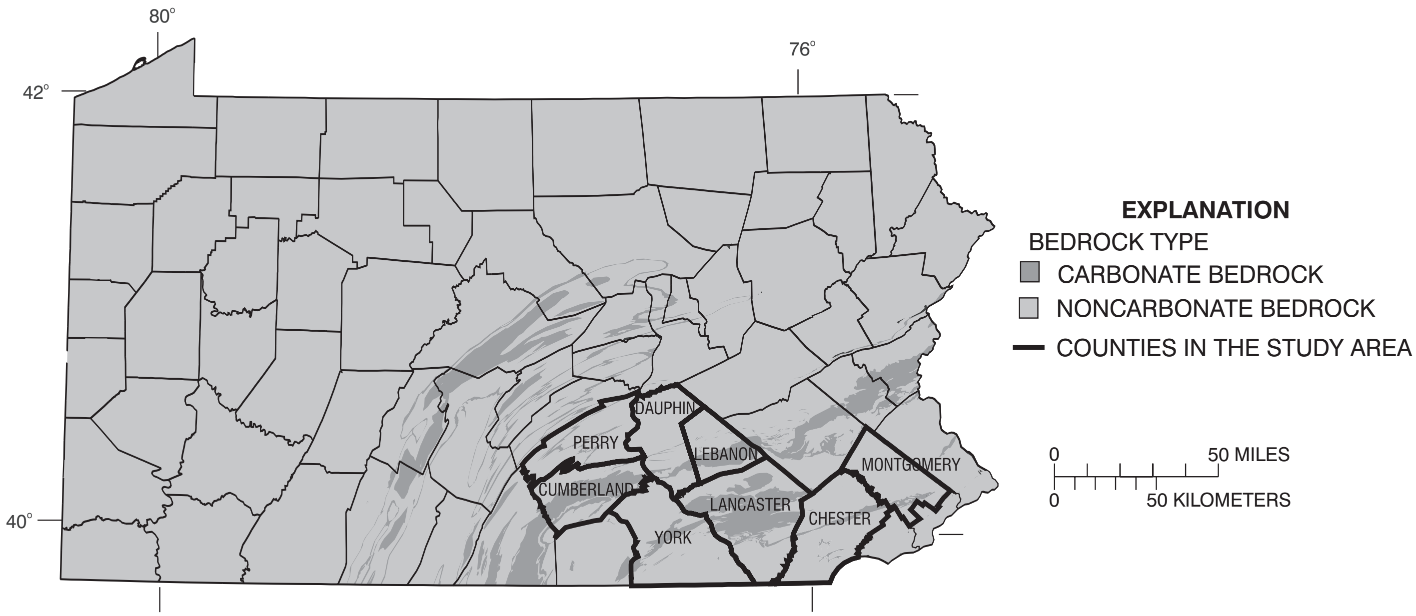

Figure 1. Location of study area in south-central and southeastern Pennsylvania and bedrock types where ground water was sampled and analyzed for total coliform and *Escherichia coli* bacteria.

Table 3. *Selected characteristics of wells sampled and their locations, south-central and southeastern Pennsylvania*

[Med, median; Max, maximum; Twp, township; Co., county; Dept., department; NAWQA, National Water-Quality Assessment Program]

Well type	Rock type	County	Data source	Number of wells sampled		Well age, in years as of 2000	Depth of wells sampled, in feet	Casing length, in feet	Depth to first water-bearing zone, in feet
Sanitary[1]	Carbonate	Cumberland	S. Middleton Twp. or well driller's records	13	19	Med: 4 Max: 16	Med: 180 Max: 260	Med: 80 Max: 84	Med: 110 Max: 210
		Perry	Well driller's records	1					
		Chester	Chester Co. Health Dept.	4					
		Dauphin	Well driller's records	1					
	Noncarbonate	Chester	Chester Co. Health Dept. or NAWQA	8	20	Med: 2 Max: 13	Med: 175 Max: 250	Med: 40 Max: 75	Med: 90 Max: 140
		Montgomery	Montgomery Co. Health Dept.	11					
		York	NAWQA	1					
Nonsanitary[2]	Carbonate	Cumberland	NAWQA, S. Middleton Twp., or well driller's records	15	20	Med: 12 Max: 23	Med: 176 Max: 250	Med: 41 Max: 89	Med: 108 Max: 220
		Dauphin	NAWQA	1					
		Lancaster	NAWQA	3					
		Lebanon	NAWQA	1					
	Noncarbonate	Chester	Well driller's records or NAWQA	6	19	Med: 20 Max: 30	Med: 150 Max: 240	Med: 40 Max: 87	Med: 62 Max: 178
		Lancaster	NAWQA	3					
		Montgomery	Well driller's records	6					
		York	NAWQA	4					
Total wells				78	78				

[1] A "sanitary" well refers to a well installed with grout the entire annulus of the casing.
[2] A "nonsanitary" well refers to a well installed with loose dirt or fill around the annulus of the casing.

WELL-CONSTRUCTION PRACTICES IN PENNSYLVANIA

Water-well construction for private household supply is not regulated in most parts of Pennsylvania. Typically, private on-lot wells are constructed as open holes completed in bedrock with minimal surface casing, little or no annular grout seal, and a loose-fitting well cap. The PaDEP has established *guidelines* for water-well construction in a Fact Sheet, “Guidelines for installing private water wells in bedrock” (Pennsylvania Department of Environmental Protection, 2000). According to these guidelines, “State law does require drillers to have a yield rig permit and a water-well drillers license” but “When a new well is drilled, no state requirements for construction materials, yield, or quality apply.” The guidelines offer recommendations for the construction of a well designed to protect the water source by including such features as a “vermin-proof” cap and casing grout (fig. 2). They also offer criteria to consider when choosing a well site, information about common “undesirable” water-quality constituents homeowners should consider having the ground water from their private wells tested for periodically, and preventative measures that homeowners can take to ensure that they do not contaminate their own water supply. Because the relatively new (2000) PaDEP guidelines are not rules or regulations, it is not known to what extent they presently are being followed or have been followed in the past.

A few counties in Pennsylvania have established countywide well-construction regulations and some townships have instituted well-construction ordinances within their municipalities. For the purposes of this report, well-construction regulations in two counties with Health Departments in southeastern Pennsylvania, Chester and Montgomery Counties, will be discussed. Both counties were targeted for sampling because they currently have well-construction regulations in place and, therefore, a database of wells with known well-construction practices. Well-construction regulations as part of a township ordinance within South Middleton Township, Cumberland County, also will be discussed. This was another area selected for sampling because of regulated well-construction practices currently in effect. Regardless of whether or not a well is constructed in a county or municipality in Pennsylvania with well-construction regulations, water-well drillers are required to submit a copy of the well-drillers’ record to the Pennsylvania Department of Conservation and Natural Resources (DCNR) for each well they construct. In all cases, it is the responsibility of homeowners to ensure the potability of their private water supply with routine testing.

Chester County

Chester County Health Department’s (CCHD) well-construction regulations have been in effect since March 21, 1983 (Chester County Health Department, 1993). A main objective in enacting these regulations is to establish minimum, countywide standards for water-well construction, monitoring wells, individual, noncommunity and community water supplies, and geothermal boreholes. All well contractors and pump-installation contractors must obtain a license to conduct business in Chester County, and in order to obtain a license, they need to pass an examination given by the CCHD. License renewal is required annually. In addition, contractors must obtain a permit before each new well is drilled, before a well is repaired or modified, and prior to installation of any pumping equipment.

The CCHD regulations specify requirements that must be met in order to maintain minimum standards for quality of water-supply wells (Chester County Health Department, 1993). The CCHD requires that the source of supply shall be from a water-bearing zone at least 25 feet below land surface. The well must be constructed at a minimum distance from potential sources of pollution that include, but are not limited to, septic tanks, sewer lines, bio-solids disposal areas, barnyards, and manure pits. The watertight casing must extend to a depth of at least 20 feet, with an additional 5 feet of casing extending into bedrock or similarly competent strata. The annular space must be filled completely with an approved grouting material such as neat cement grout, concrete grout, sand cement grout, or bentonite grout. The well casing must extend a minimum of 12 inches above finished land surface. Upon completion of installation, the well must be pumped until the discharged water runs clear. To disinfect the well, pump, piping, and fixtures, they must be filled with a solution of water containing at least 100 parts per million of free chlorine. A portion of the solution shall be recirculated to the well to insure proper agitation. The well may not be used for a period of 24 hours. All required information must be submitted on the appropriate form to the CCHD within 30 days of completion of well drilling.

The CCHD recently revised its well-construction regulations, and it is now mandatory (as of March 9, 2001) that all wells drilled in Chester County be completed with a sanitary sealed well cap (Chester County Health Department, 1993). The revised regulations also state that a sanitary sealed well cap must replace the present well cap when the well or pump warrant repair. A typical loose-fitting well cap and a common type of sanitary sealed well cap are shown in figure 3.

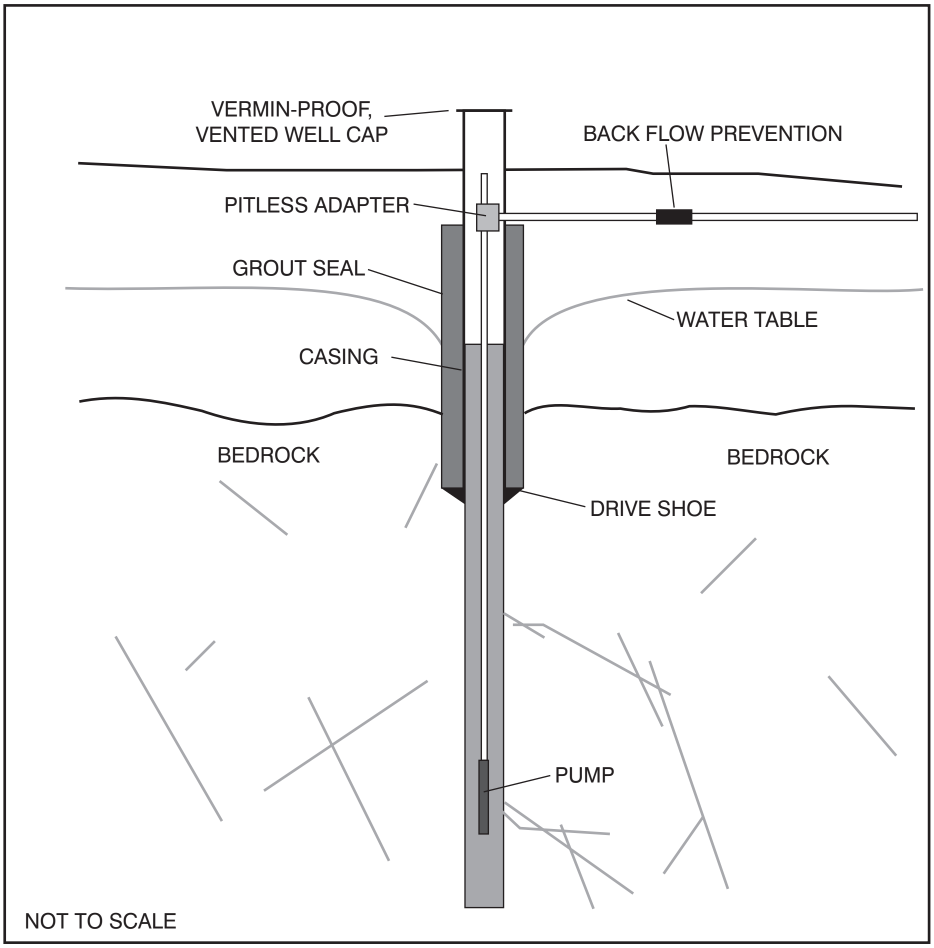

Figure 2. Cross-section of a ground-water well. (Used with permission from “Guidelines for Installing Private Water Wells in Bedrock,” Pennsylvania Department of Environmental Protection, 2000. For more information, go to: *http://www.dep.state.pa.us* and enter “Private Wells” in the Direct Link box.)

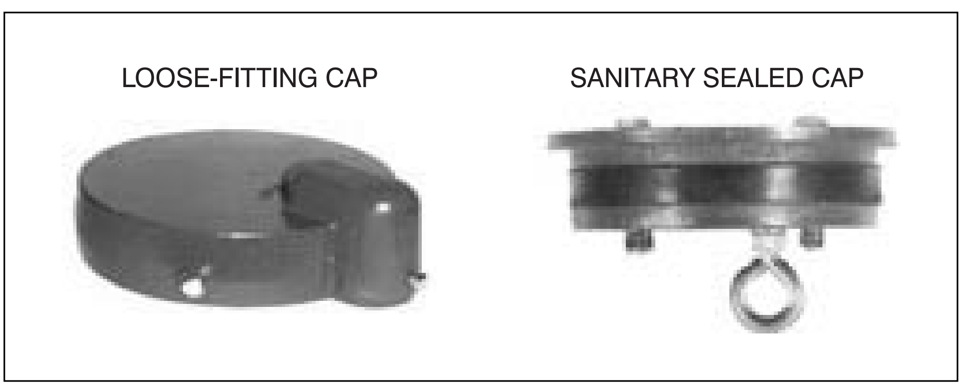

Figure 3. Loose-fitting and sanitary sealed well caps for 6-inch wells.

Montgomery County

Montgomery County Health Department's (MCHD) well-construction regulations have been in effect since February 1, 1997 (Montgomery County Health Department, 1997). By law, in Montgomery County, permits to construct a well must be obtained prior to installation or modification of any individual water-supply well. Water-well drillers must have a DCNR license to construct wells for individual water supply.

Chapter 17, Individual Water Supply System Regulations, of the Montgomery County Public Health Code (Montgomery County Health Department, 1997) aims to establish the standards for location, construction, modification, and abandonment of individual water-supply wells to protect public health and welfare. Section 17-7 of the regulations refers to the minimum isolation distances from possible pollution sources. According to the construction specifications set forth by the MCHD, the casing must extend a minimum of 30 feet below land surface or 5 feet into bedrock or competent strata (whichever is deeper). Also, the casing must be grouted in place. The annular space between the well casing and the earth formation must be completely filled with an approved grout material such as neat cement grout, sand cement grout, or bentonite or sealing clay. This filling is done in order to prevent the entrance of pollution from surface runoff or polluted aquifers (Montgomery County Health Department, 1997). The casing must be steel, unless written permission from the MCHD has been granted for the use of alternate casing types. The casing shall extend a minimum of 12 inches above the finished land surface, or a proper height that would be necessary to prevent surface contamination, whichever is greater. After completion of well construction and pump installation, the well shall be pumped until the discharged water is clear. The well, pump, piping, and other fixtures then must be filled with a concentration of at least 50 parts per million of free chlorine in order to disinfect. The solution shall be properly agitated by recirculating a portion of it directly to the well; the well should not be used for 24 hours. The grout information and other required data must be submitted to MCHD by the DCNR-licensed water-well driller within 30 days of completion of the well drilling process.

South Middleton Township

The South Middleton Township Well Ordinance No. 98-22 has been in effect since October 20, 1998 (Board of Supervisors of South Middleton Township, 1998). The ordinance intends to protect the quality of domestic water supply and maintain the minimum isolation distance between water supplies and sources of possible contamination such as agricultural fields (50 feet) and sewage disposal systems (100 feet from a sewage drain field or absorption system and 50 feet from a septic tank, distribution tank, and (or) pump box). A sewage permit must be obtained before a water-supply well permit can be issued. Water-supply well permits must be obtained from the Codes Enforcement Officer prior to the installation of a well or major repair to a present well. The water-well driller must be licensed by the Commonwealth of Pennsylvania and provide a copy of required information to South Middleton Township upon completion of the well construction.

The following standards apply to well construction in South Middleton Township (Board of Supervisors of South Middleton Township, 1998). The casing must be a minimum of 20 feet below the finished grade and extend 10 feet into bedrock or other competent strata. The annular space shall be filled completely with cement grout or an equivalent sealing material from the bottom of the casing to within 5 feet of the land surface. A tremie pipe and a grout pump are used for external grouting, and the casing shall be sealed against entrance from potentially contaminated water-bearing formations. The top of the casing must extend a minimum of 24 inches above land surface, and surface drainage must be diverted away from the well. A well cover must overlap the outside of the well casing at least 2 inches. The source of the water supply shall be from a water-bearing formation of at least 100 feet below land surface, unless a formation yields a discharge of 6 gallons per minute at a lesser depth.

STUDY METHODS

Water samples were collected from private, household-supply wells for bacteriological analysis from September 2000 to March 2001. Ground water from each of 78 wells was sampled one time for this study. Wells chosen generally were less than 250 feet deep and generally less than 25 years old. The project was designed to analyze for presence of bacteria in water from wells of "sanitary" construction and water from wells of "nonsanitary" construction. A "sanitary" well was defined as a well that had been installed with a sanitary sealed well cap and with grout along the entire annulus of the casing. A "nonsanitary" well was defined as a well constructed with loose dirt or fill around the annulus of the casing and a loose-fitting well cap. It was obvious a few months into the study that wells within the study area installed with a sanitary sealed cap were rare. Consequently, the definition of a "sanitary" well was modified to mean wells constructed with grout installed along the entire annulus of the casing.

Site Selection

Sites were selected for this study on the basis of a field inventory of candidate wells conducted to verify well locations with respect to bedrock type and to document the land-use and well characteristics that could be the source of bacteria or promote its movement into the well. Approximately one-third of the well sites selected previously were sampled as part of the USGS LSUS NAWQA Program. Only wells on sites adjacent to agricultural land-use areas were targeted for bacteriological sampling in this study. Once a good candidate well was found, permission to sample the well was obtained. An attempt was made to pair wells with sanitary and nonsanitary construction with similar rock type and site-specific and regional land-use characteristics.

An equal number of wells with sanitary and nonsanitary construction were selected for sampling for total coliform and *E. coli* in each of two geologic settings: areas underlain by carbonate rocks and areas underlain by noncarbonate rocks. The well-selection matrix shown in table 3 includes information on the location of the 78 wells selected for inclusion in this study, as well as the data sources used to locate the wells and selected characteristics of those wells.

Wells were selected for this study using a variety of resources. Wells with sanitary construction in areas underlain by noncarbonate bedrock were found by searching well records in the CCHD and MCHD and by obtaining permission to sample a well in York County previously sampled as part of the LSUS NAWQA Program. In Montgomery County, well regulations were enacted in 1997; thus, wells of recent construction could be found with sanitary and conventional (nonsanitary) construction. Sanitary wells in Montgomery County, located by searching MCHD records, were paired with nonsanitary wells (located by well driller's records) constructed in areas underlain by noncarbonate bedrock in areas of similar agricultural land use. In Chester County, regulations have been in place for nearly 20 years; thus, recently constructed wells all have sanitary construction. Sanitary wells in Chester County in areas underlain by noncarbonate bedrock were paired with wells of nonsanitary construction in areas of similar agricultural land use and rock type in neighboring Lancaster and York Counties. The nonsanitary wells selected for sampling in Lancaster and York Counties in areas underlain by noncarbonate bedrock previously were sampled as part of the LSUS NAWQA Program. It was extremely difficult to locate wells of sanitary construction in areas underlain by carbonate bedrock. For this reason, a single township was heavily targeted, South Middleton Township, because a well-construction ordinance currently is in place within the township (enacted 1998). Other wells with sanitary construction in areas underlain by carbonate bedrock were found in Chester County by searching CCHD files and in Perry and Dauphin Counties by searching well driller's records. Nonsanitary wells drilled in areas underlain by carbonate bedrock were found in (1) Cumberland County by searching well driller's records and by obtaining permission to sample wells previously sampled as part of the LSUS NAWQA Program, and (2) in Dauphin, Lancaster, and Lebanon Counties by obtaining permission to sample wells previously sampled as part of the LSUS NAWQA Program.

Sample Collection and Analysis

Water samples were collected for analysis of two indicator bacteria (total coliform and *E. coli*). Total coliform bacteria was chosen because it is used as an EPA drinking-water standard for public supplies (there are no national standards for household-supply wells), even though its presence may be of nonfecal origin such as that found naturally in soils, plants, and other media. *E. coli* bacteria was chosen because it is a species of the coliform group exclusively of fecal origin. Therefore, *E. coli* bacteria serves as a more direct indicator of fecal contamination and the possible presence of enteric pathogens (U.S. Environmental Protection Agency, 2000). Indicator bacteria were chosen because they are not usually pathogenic; however, their presence in drinking water indicates the possible presence of pathogens.

The USGS used the standard plate count membrane-filter method for enumeration of total coliform on m-Endo media and *E. coli* bacteria on NA-MUG media. In this procedure, the sample aliquot was passed through a membrane filter with a pore size of 0.45 micrometer. After the aliquot was passed through the membrane filter, the filter was aseptically placed on a sterile 50 millimeter petri dish containing m-Endo medium. The petri dish with the membrane filter then was placed in an incubator at 35°C for 22 to 24 hours. If total coliform bacteria were present in the sample, individual cells on the membrane filter multiply after the proper incubation time. Each colony counted represents the single bacteria cell from which it originated. The membrane filters having colonies that exhibit a golden-green metallic sheen are positive for total coliform bacteria (Britton and Greeson, 1989). If total coliform bacteria were present, the membrane filter was aseptically transferred to a 50 millimeter petri dish containing NA-MUG medium and incubated for a period of 4 hours at 35°C. Colonies that produce a bright blue fluorescent perimeter around a darker colony under ultraviolet light are positive for *E. coli*. The result is reported as number of colonies per 100 mL (milliliter) of sample (U.S. Environmental Protection

Agency, 1991). Both m-Endo and NA- MUG mediums are approved by the EPA for analysis of drinking and source waters (U.S. Environmental Protection Agency, 1991). Total coliform bacteria media and sterile buffered water were obtained from the USGS Water-Quality Supply Unit in Ocala, Fla. *E. coli* bacteria media was a Difco Brand obtained from Fisher Scientific. Media from both entities was quality assured prior to shipment.

The Colilert method (Clesceri and others, 1998), performed by the PaDEP on sequential replicate samples collected for quality control, uses multiple dilution tubes in order to determine the most probable number of total coliform and *E. coli* in water samples. A serial dilution is performed on an aliquot of sample, and the appropriate volume is placed in tubes containing nutrient broth and indicator chemicals. The result, number of total coliform or *E. coli* colonies per 100 mL, is a statistical estimate of the mean density of bacteria in a water sample. The MPN is derived from a table that is based on the number of sample tubes testing positive (Clesceri and others, 1998).

Samples were collected one time only at each site from an outside faucet that bypassed any water-treatment systems such as a chlorination system, water softener, ultra-violet light, charcoal filter, and others. The types of samples collected included routine sample aliquots at each site and additional split and sequential replicate sample aliquots at 21 of the 78 sites for quality-control purposes. The goal was to obtain an ideal colony count (20-80 colonies per 100 mL) for total coliform and *E. coli* bacteria where possible. Combinations of 200 mL, 100 mL, or 10 mL aliquots were filtered for each ground-water sample in an attempt to obtain bacteria detections. The decision to filter aliquots was made on the basis of previous experience testing for bacteria in ground water and that bacteria detections generally are rare in small sample volumes of ground water, especially in the ideal colony count range. All samples were collected in 1-liter glass bottles that had been autoclaved prior to use. Water samples were collected after purging a minimum of one well volume of water and obtaining stable measurements for pH, specific conductance, dissolved oxygen, and temperature. Water samples were immediately processed at the site using membrane filtration techniques (Myers and Sylvester, 1997). Sample processing and analyses for bacteria were done by USGS personnel in the Pennsylvania District Office with the exception of 9 sequential replicates that were done at approximately 10 percent of the sites and sent to PaDEP personnel for processing within 24 hours at the PaDEP Laboratory in Harrisburg, Pa.

Quality Assurance

For quality control, split replicate and (or) sequential replicate aliquots (combinations of 200 mL, 100 mL, or 10 mL aliquots) were collected at 21 of the 78 sites and resulted in an additional 28 samples (table 4). Split replicates are samples collected in the same bottle and divided into subsamples for identical analyses. They are collected to assess reproducibility in sample-processing results. Sequential replicates are collected consecutively (instead of simultaneously) in two or more bottles and are used to assess variability among samples resulting from sample collection (Wilde and others, 1999).

Replicate samples at 15 of the 21 sites where quality-control samples were collected were split replicate sample aliquots done by the USGS. Sequential replicate sample aliquots were collected and analyzed by the USGS at an additional four sites. Bacteria concentrations in the routine samples and the replicate samples generally were similar (table 4). There were a few exceptions but differences typically were at the detection limit. For example, data for the routine sample would indicate that there was one total coliform and (or) *E. coli* colony per 100 mL, whereas the replicate sample would not have any bacteria detections or opposite. Because this occurs is not surprising. As was stated previously, bacteria detections—especially bacteria colonies in the ideal range—generally are rare in small sample volumes of ground water. This resulted once for total coliform and 5 times for *E. coli* when comparing USGS environmental data and USGS split and sequential replicate data at those 19 sites. Because these differences were at or very near the detection limit indicates the reproducibility of results by the USGS is good. It also indicates the USGS sample-collection methodology is consistent.

The PaDEP analyzed sequential replicate samples from 9 of the 21 sites where quality-control samples were collected. These replicates were processed to assess reproducibility of results between laboratories. Total coliform bacteria were found at one site and *E. coli* bacteria at two sites by the USGS but not by the PaDEP at those same sites. Similarly, the PaDEP found total coliform bacteria at a site that the USGS did not. These differences could most likely be explained by the difference in methodologies between the two agencies as discussed above. The PaDEP data indicate the most probable number using the Colilert method; the USGS data indicates an actual colony count using the membrane-filter method. These quality-control analyses were done to confirm the presence / absence of bacteria with another laboratory.

***Table 4.** Comparison of U.S. Geological Survey environmental sample data to U.S. Geological Survey replicate sample data and Pennsylvania Department of Environmental Protection replicate sample data*

[USGS, U.S. Geological Survey; PaDEP, Pennsylvania Department of Environmental Protection; mL, milliliters; <, less than; TNTC, too numerous to count; --, bacteria was not analyzed at this sample volume; split replicate results are shown in light gray and sequential replicate results are shown in dark gray]

Site identifier	USGS environmental sample		USGS replicates		PaDEP replicates	
	Total coliform 100 mL	*E. coli* 100 mL	Total coliform 100 mL	*E. coli* 100 mL	Total coliform 100 mL	*E. coli* 100 mL
394606076002001	<1	--	<1	--	<1	<1
400945077104201	1	1	1	<1	1	<1
400854077112701	23	1	21	<1	53	<1
400805077074101	3	<1	2	<1	<1	<1
400854077161801	3	<1	4	1	16	1
400711076113801	5	<1	4	<1	<1	<1
400827077083101	<1	--	<1	--	1	<1
401735075293001	10	<1	--	--	16	<1
400229076020301	<1	--	--	--	<1	<1
401125077195801	11	<1	3	<1	--	--
400515077205501	1	<1	<1	--	--	--
400746077262201	2	1	2	<1	--	--
401750076274601	TNTC	TNTC	TNTC	TNTC	--	--
401445076440801	39	4	44	3	--	--
400824077085501	1	<1	1	<1	--	--
395204076262101	<1	--	<1	--	--	--
400834077134401	<1	--	<1	--	--	--
401744075312801	<1	--	<1	--	--	--
401316077023001	3	1	3	1	--	--
401046077094601	6	<1	4	1	--	--
401254076114701	1	<1	2	<1	--	--

Blank samples of sterile water also were collected for quality control and were filtered prior to the environmental sample at each site. Blanks were 100 mL of sterile buffered water (sterile phosphate buffer solution with peptone) that were processed with the sterilized equipment. The blank samples were analyzed to determine the effectiveness of the sterilization procedures. All the blank samples of sterile water that were analyzed were free of bacteria detections with the exception of one sample. The blank at one site had one total coliform colony that formed on the 100 mL plate. The associated USGS routine sample data (10 colonies per 100 mL) was not excluded as a result of this because a PaDEP sequential replicate sample (collected in another bottle) also was analyzed for this site that produced a similar result (16 colonies per 100 mL).

Statistical Analysis

Nonparametric statistical analyses were conducted to determine relations between bacteria concentrations and discrete variables (also known as categorical variables) such as bedrock type, whether or not the well was grouted, and combinations of both variables. Statistical tests were chosen on the basis of the amount of censored data for each bacteria type. Censored data are data that include concentrations that are essentially “nondetects”—detected at levels below (less than) a set detection limit. The detection limit used for both total coliform and *E. coli* bacteria was 1 colony per 100 mL. Therefore, anything less than 1 (zero) colony per 100 mL constitutes a “nondetect” of bacteria. An alpha value of 0.05 was used for all statistical analyses. If statistical analyses indicate an alpha value of 0.05 or less, there is a 95-percent chance an association is present mathematically among the variables being compared.

Kruskal-Wallis tests were used when less than 50 percent of the data were censored. The Kruskal-Wallis test was computed by ranking a continuous variable (in this case the bacteria concentrations) and then testing for differences in the medians of the ranks among categorical variables. This test was used on the total coliform data set because 38 percent of the data were censored.

Contingency tables were used when greater than 50 percent of the data were censored. This method of statistical analysis measures the association between two nominal (no ordering such as high, medium, low) categorical variables (Helsel and Hirsch, 1992). The bacteria concentration data were converted to a present / absent variable and analyzed to determine if this variable was independent of another variable or variables (bedrock type, grout / no grout). This test was used on the *E. coli* data set because 90 percent of the data were censored. Two conditions are necessary for the test to be valid: All the cells must have an expected number of observations greater than one, and at least 80 percent of the cells must have an expected number of observations greater than five (Helsel and Hirsch, 1992, p. 381). An example of a 2 × 2 contingency table matrix set up to show whether or not the presence of *E. coli* bacteria is related to bedrock type is given in table 5.

Table 5. *Sample contingency table matrix for comparing the presence/absence of E. coli and bedrock type*

Number of sites with *E. coli* present in areas underlain by carbonate bedrock	Number of sites with *E. coli* present in areas underlain by noncarbonate bedrock
Number of sites with *E. coli* absent in areas underlain by carbonate bedrock	Number of sites with *E. coli* absent in areas underlain by noncarbonate bedrock

Spearman’s rank correlation was used to analyze two or more continuous variables to determine whether or not there was a linear association between the two variables. This method may be used when both variables are censored (Helsel and Hirsch, 1992, p. 374) and is done by first ranking each variable separately and then calculating the Spearman’s rank correlation coefficient for the ranks (Ott, 1993). Ranking of the data ensures the full extent of the monotonic relation (y increases, or decreases, with x) is analyzed. As stated above, an alpha of 0.05 was used in the analyses. If the probability from Spearman's correlation test is less than alpha, there is a 95-percent chance an association is present mathematically between the variables. Spearman’s rho was used to determine the strength of this association among total coliform or *E. coli* bacteria and other continuous variables (values are on a continuous scale) such as well depth, casing length, well age, and depth to the first water-bearing zone.

RELATION BETWEEN SELECTED WELL-CONSTRUCTION CHARACTERISTICS AND OCCURRENCE OF BACTERIA IN GROUND WATER

Waters from about 48 of the 78 wells sampled (62 percent) for this study contained total coliform bacteria. *E. coli* bacteria were detected in waters from 8 of the same 78 wells (10 percent). Seventeen percent of the samples that were positive for total coliform also were positive for *E. coli*. In contrast, neither total coliform nor *E. coli* bacteria were found in waters from 30 of 78 wells sampled (38 percent). All samples were collected from wells adjacent to agricultural land-use areas. The bacteriological data from this study is presented in appendix A.

Percentages of total coliform and *E. coli* bacteria found in sanitary and nonsanitary wells and in wells completed in carbonate and noncarbonate rocks are shown in figure 4. Total coliform bacteria were just as likely to be found in sanitary wells (nearly 60 percent) as in nonsanitary wells (nearly 65 percent). The areas underlain by carbonate bedrock had the highest percentages of total coliform detected (about 75 percent) but nearly half of the samples collected in the areas underlain by noncarbonate bedrock were found to have total coliform present as well. *E. coli* bacteria were found in 15 percent of the nonsanitary wells compared to 5 percent of the sanitary wells and only were found in areas underlain by carbonate bedrock.

The locations of the wells sampled and the distribution of the presence of total coliform and *E. coli* bacteria in the waters of those wells (both sanitary and nonsanitary) are shown in figures 5 and 6, respectively. Total coliform detections were uniformly distributed throughout the study area. Conversely, *E. coli* detections were concentrated in the areas underlain by carbonate bedrock predominantly in the nonsanitary wells (fig. 6). These distribution patterns are consistent with the LSUS NAWQA Program findings (Bickford and others, 1996).

Statistical tests for this study were conducted to determine if the presence of bacteria was related to categorical variables such as bedrock type, whether or not a well was grouted, and combinations of the two variables at a 95-percent confidence interval. These tests were done in an effort to assess aquifer vulnerability to bacterial contamination by determining the bacteriological quality of water from wells constructed in varying bedrock types (carbonate and noncarbonate) and the effect, if any, that different well-construction characteristics have on the quality of the drinking water supply.

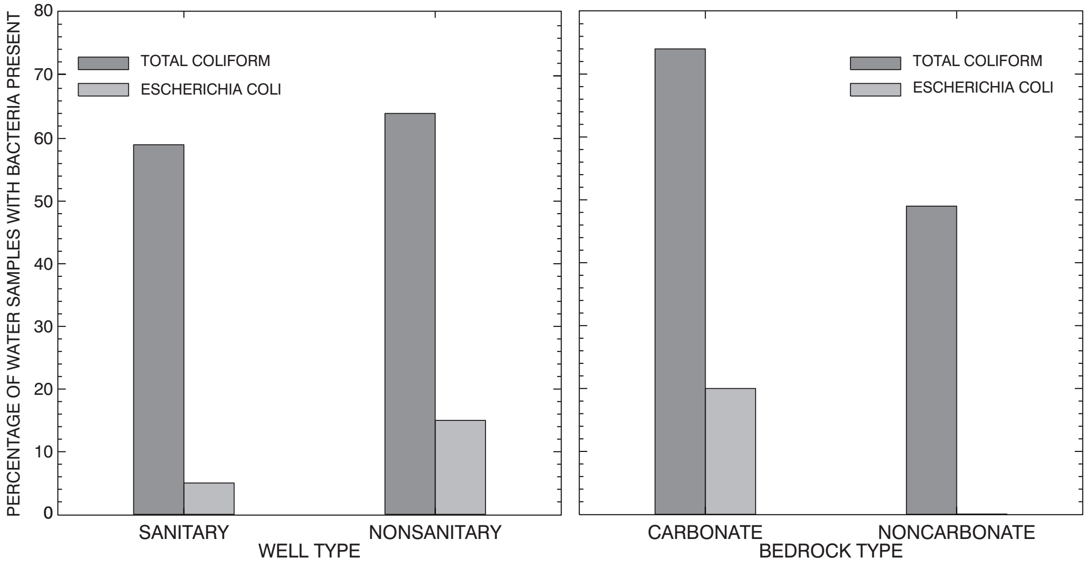

Figure 4. Bacteria presence by well-construction characteristic and bedrock type from wells sampled, south-central and southeastern Pennsylvania.

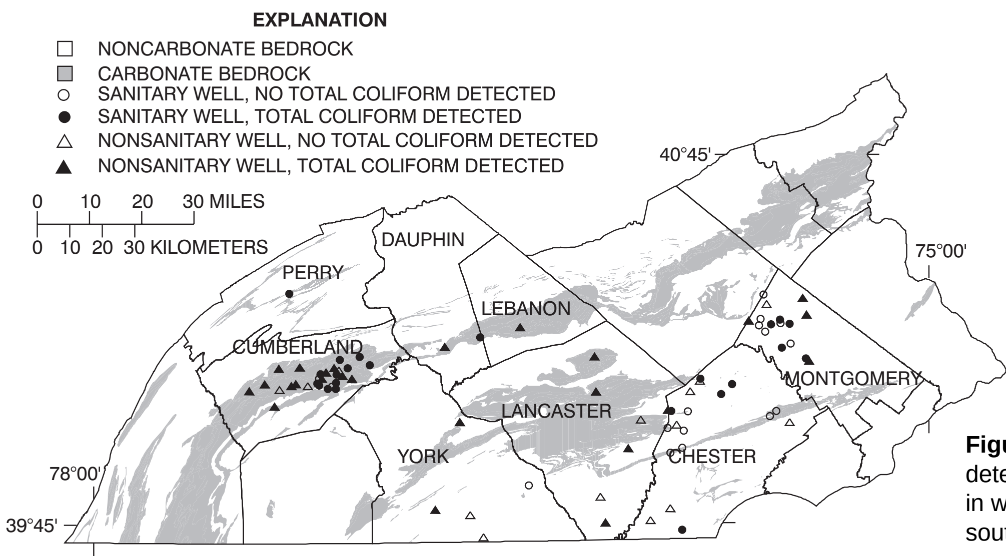

Figure 5. Sampling locations and detections of total coliform bacteria in wells sampled, south-central and southeastern Pennsylvania.

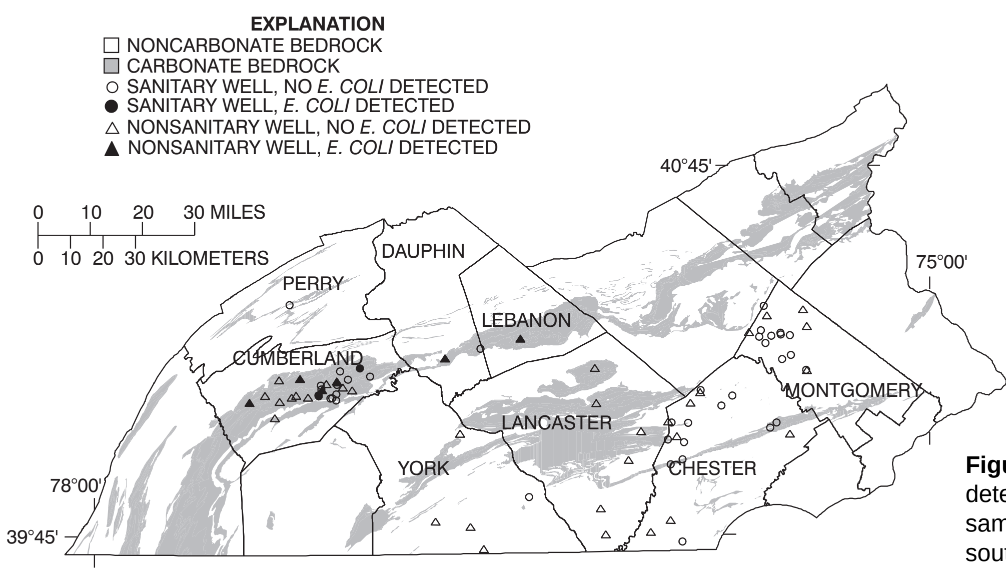

Figure 6. Sampling locations and detections of *E. coli* bacteria in wells sampled, south-central and southeastern Pennsylvania.

Sanitary and Nonsanitary Construction

Bacteria concentrations were compared among wells constructed using different well-construction characteristics. Concentrations in wells with grout (sanitary) installed along the entire annulus of the casing and without grout (nonsanitary) were compared. The range in concentrations and median concentrations of total coliform in both types of wells were similar (fig. 7). The results of this comparison for total coliform do not indicate a statistically significant difference. Boxplots are not shown for *E. coli* because of the small number of detections. *E. coli* was more likely in water from nonsanitary wells than in water from sanitary wells. Seventy-five percent of the *E. coli* bacteria detected was observed in water from wells of nonsanitary construction.

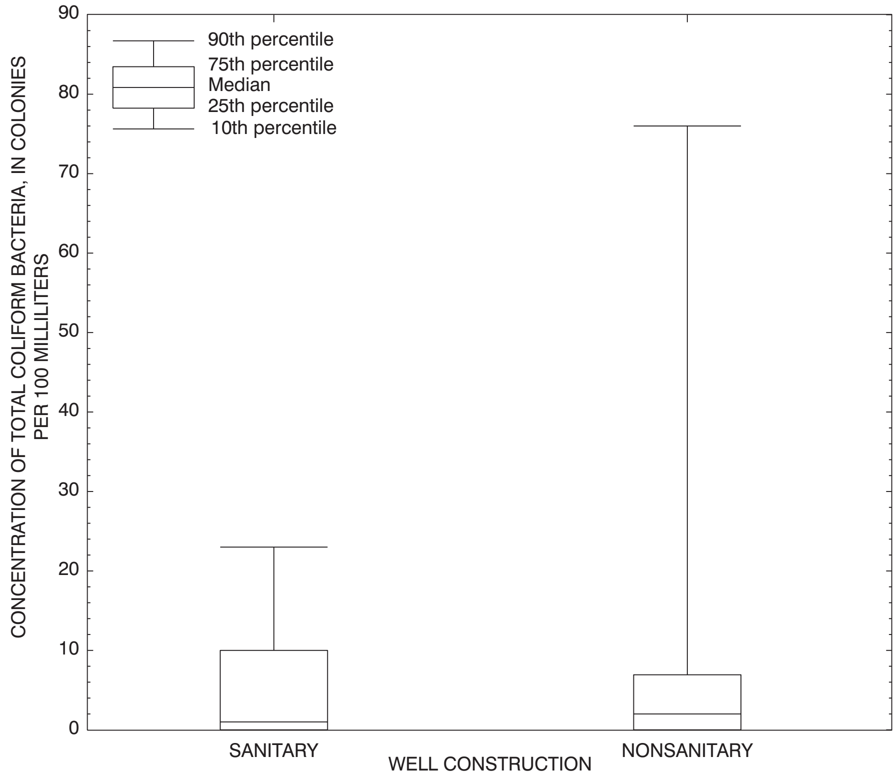

Figure 7. Concentrations of total coliform bacteria in sanitary and nonsanitary wells, south-central and southeastern Pennsylvania.

Bedrock Type

Comparisons also were made between the presence of bacteria and wells constructed in areas underlain by carbonate and noncarbonate bedrock. The range in concentrations and median concentrations for total coliform bacteria from wells are similar between bedrock types (fig. 8). Therefore, this relation is not statistically significant for total coliform. As stated earlier, boxplots are not shown for *E. coli* because of the small number of detections, but all of the *E. coli* detections (100 percent) were observed in ground water from wells underlain by carbonate bedrock. This observation indicates high aquifer vulnerability to *E. coli* bacteria contamination in carbonate bedrock.

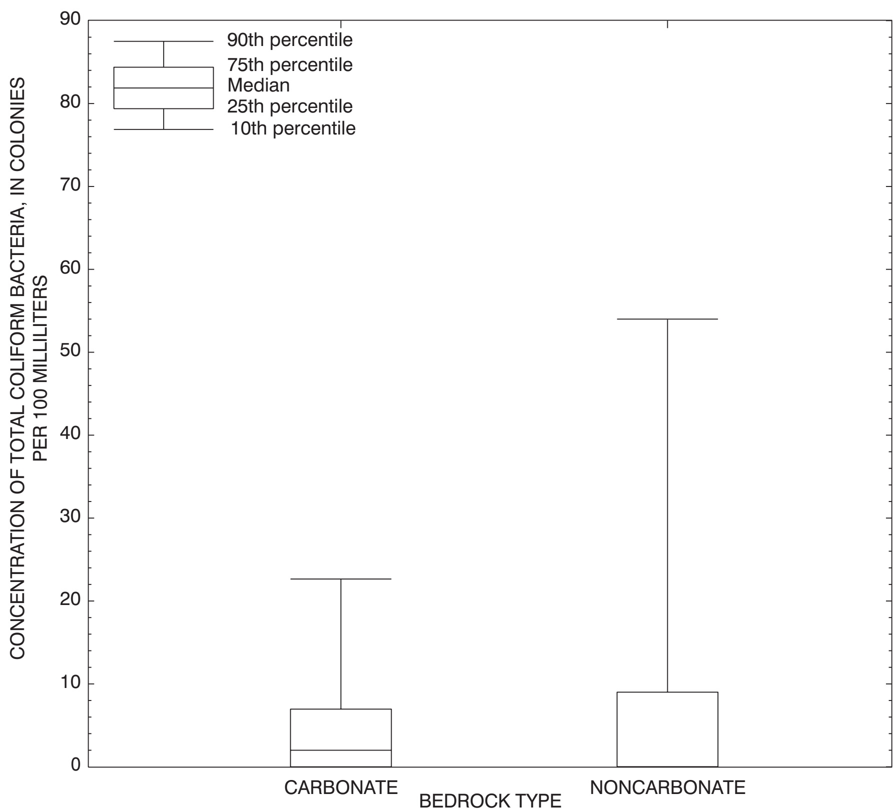

Figure 8. Concentrations of total coliform bacteria in wells constructed in areas underlain by carbonate and noncarbonate bedrock, south-central and southeastern Pennsylvania.

Bacteria concentrations also were compared to the combined effects of well-construction practices and bedrock type—sanitary wells in carbonate bedrock, sanitary wells in noncarbonate bedrock, nonsanitary wells in carbonate bedrock, and nonsanitary wells in noncarbonate bedrock. The results of these comparisons for total coliform do not indicate statistically significant differences among the four groups (fig. 9). Again, because of the small number of *E. coli* bacteria detections, boxplots are not shown. *E. coli* bacteria, however, were detected more frequently in water from nonsanitary wells in areas underlain by carbonate bedrock.

Seasonal Effects

Comparisons were made between bacteria data from waters of 26 wells sampled for this study that also were sampled as part of the LSUS NAWQA Program to determine if bacteria presence had any seasonal variation. Bacteria concentrations in 17 of the 26 wells were found to be lower for this study than when sampled for the NAWQA Program (1993–95). Further breakdown of the data from those 17 wells indicates that both the total coliform and *E. coli* concentrations were lower for this study than for the LSUS NAWQA Program. Data from 11 of the 17 wells indicates lower total coliform concentrations for this study (7 of them are now free of total coliform) than for the LSUS NAWQA Program, but *E. coli* concentrations remained relatively unchanged. The fact that such a high percentage of the sites analyzed had lower concentrations for this study than for the LSUS NAWQA Program can most likely be explained by the seasons in which sampling took place. The LSUS NAWQA Program samples were collected from June to August in the summers of 1993–95 during the growing season when manure is applied to fields. Samples were collected for this study in the fall of 2000 and the winter of 2001 after the growing season was over and manure application to fields was not occurring. Higher total coliform concentrations were detected in water from 7 of the 26 wells for this study than when they were sampled as part of the LSUS NAWQA Program. On closer inspection, however, five of those samples had total coliform concentrations that were close to the detection limit of less than 1 colony per 100 mL. *E. coli* concentrations for all seven of these wells remained unchanged. Two sites sampled for both studies had samples that were now grossly contaminated with total coliform; one of the two also was contaminated with *E. coli*. The site that was grossly contaminated with total coliform and *E. coli* for this study is a nonsanitary well in an area underlain by carbonate bedrock that did not have detections of either bacteria type during the LSUS NAWQA Program. Possible explanations for the high number of bacteria now present in this well could include physical defects now present in the well such as leakage around the pitless adapter and a cracked or corroded casing (fig. 2). Because the top of the casing is not sealed and the annulus around the outside of the casing for this well is not grouted, the bacteria could be a direct result of surface contamination. A failing septic system is another potential contamination source.

Comparisons also were made between bacteria data collected for a national NAWQA Program (Francy and others, 2000), the LSUS NAWQA Program (Bickford and others, 1996), and this study. Differences in percentages of bacteria are shown in figure 10. The

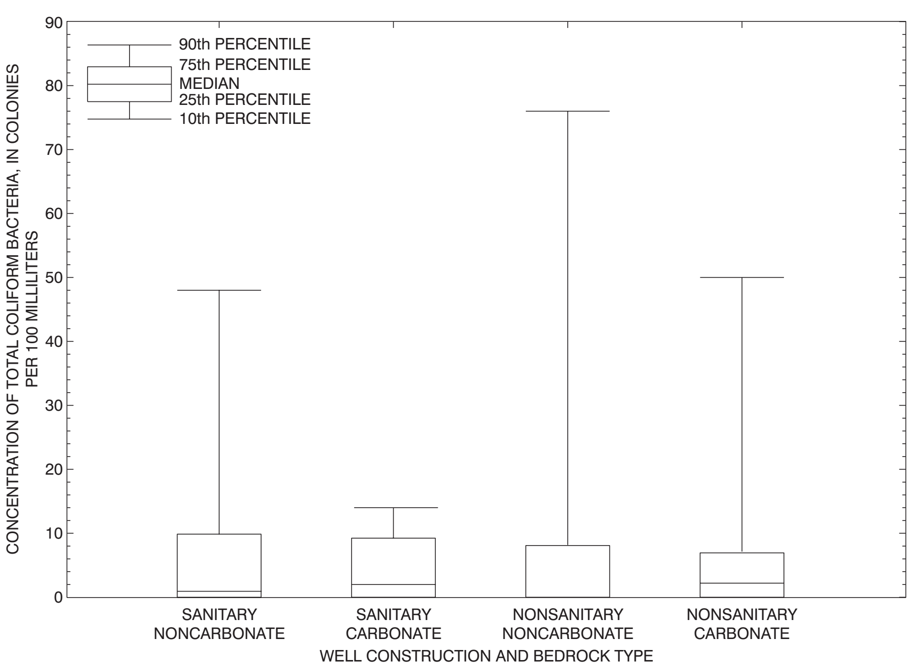

Figure 9. Concentrations of total coliform bacteria in sanitary carbonate, sanitary noncarbonate, nonsanitary carbonate, and nonsanitary noncarbonate wells, south-central and southeastern Pennsylvania.

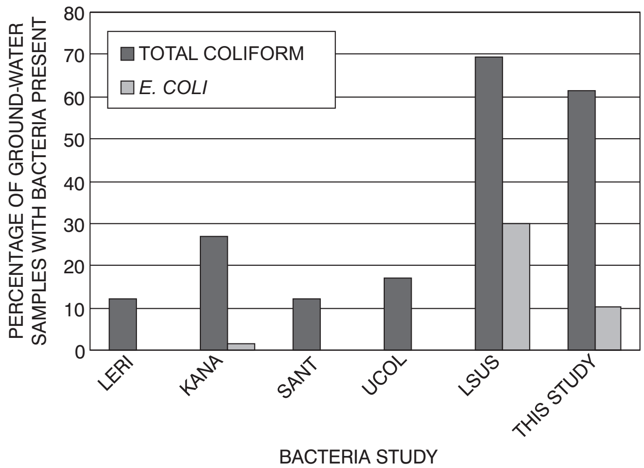

Figure 10. Percentage of detections of total coliform and *E. coli* in bacteria studies done in five National Water-Quality Assessment Program basins (Francy and others, 2000; Bickford and others, 1996) compared to this study. [LERI, Lake Erie–Lake St. Clair Basin; KANA, Kanawha–New River Basin; SANT, Santee Basin and coastal drainage; UCOL, Upper Colorado Basin; LSUS, Lower Susquehanna River Basin]

LSUS NAWQA Program took place predominantly in Pennsylvania as did this study focusing on well construction. Both Pennsylvania studies were analyzing exclusively water from private, household-supply wells. The national NAWQA Program focused on a combination of present private, household-supply, community, and noncommunity wells. Percentages of total coliform bacteria detected in the LSUS NAWQA and this study (69 and 62 percent, respectively) were well above the percentages found in the national study (LERI, KANA, SANT, and UCOL NAWQA studies). *E. coli* bacteria detections were observed mainly in Pennsylvania and were not present in the national NAWQA study. The KANA Basin was the only basin where *E. coli* was observed in the national study. The reason bacteria detections were so much higher in Pennsylvania compared to the other areas sampled could not be quantified. Differences in soils, geologic features, and well-construction characteristics could be the reason (or part of the reasons) for these detections.

Other Well-Construction Characteristics

Statistical tests also were conducted to determine if there was a relation between the concentrations of bacteria and selected well-construction characteristics such as well depth, casing length, well age, and depth to the first water-bearing zone. Spearman's correlations were used to analyze the data, and relations exist if probabilities were less than 0.05. Strong relations are indicated by high Spearman's rho values and weak relations are indicated by low Spearman's rho values.

Few significant correlations were observed with the Spearman's correlation test. The correlations that were found were for total coliform bacteria. Looking at the entire data set, there was a positive relation between concentrations of total coliform bacteria in water from the nonsanitary wells and the depth to the first water-bearing zone. This positive relation means that as the depth to the water-bearing zone increased, the total coliform concentrations increased. Further analyses were done by independently analyzing each of the four groups on the basis of sanitary construction and bedrock type. This breakdown of the data showed concentrations of total coliform had a negative correlation to water-bearing zone in the sanitary wells in areas underlain by noncarbonate bedrock. In other words, total coliform concentrations decreased with increasing depth to water-bearing zone. In addition, concentrations of total coliform had a positive correlation to water-bearing zone in the sanitary wells in areas underlain by carbonate bedrock. So for those wells, total coliform concentrations increased with increasing depth to water-bearing zone. A negative correlation is what would be expected with bacteria concentrations decreasing in deeper water-bearing zones because of the filtering of the water and the bacteria die-off rate with longer traveltimes. However, because flow in carbonate bedrock is controlled by conduit flow, water produced from deeper water-bearing zones has not necessarily undergone more filtration, nor does it have a longer residence time. Therefore, bacterial concentrations would not necessarily decrease with depth to water-bearing zone, and in this data set, bacterial concentrations actually increase with depth to water-bearing zone.

The Spearman's correlation test also showed concentrations of total coliform bacteria had a negative correlation to casing length in water from nonsanitary wells in areas underlain by noncarbonate bedrock. Again, this negative correlation is what would be expected with bacteria concentrations decreasing in deeper water-bearing zones because of the filtering of the water and the bacteria die-off rate with longer traveltimes.

Because the number of wells with sanitary seals found during this study was minimal, it was not possible to compare the occurrence of bacteria among wells with and without this well-construction feature. However, detailed information on the condition of individual wells was recorded during field visits and this information was used as a surrogate of the effects of unsealed well caps on bacteria detections. Upon removing the well cap to make water-level measurements, observations on the presence of insects were recorded by sampling crews. This information was somewhat subjective; however, the presence of insects was obvious. Of the 78 wells sampled, 38 wells had evidence of insects inside the well cap, on the wiring, plumbing, or inside the casing. Bacteria were present in wells with evidence of insects inside the well slightly more than in wells without evidence of insects. Statistical tests (contingency tables) comparing the presence of bacteria to presence of insects showed no statistically significant differences. When the data were broken down into smaller subsets on the basis of bedrock type, grout, or combinations of both, no additional significant relations were observed. Although the presence of bacteria was not significantly related to the presence of insects, this result does not indicate that a sanitary seal is not important. Only six of the wells actually were sealed. The reason for lack of correlation among wells with and without insects may be because the presence of insects is not a good surrogate for a sanitary seal (insects may have been present but not observed). Also, a combination of grout, bedrock type, and lack of a sealed well cap may all be characteristics affecting bacterial contamination. The evidence that insects (earwigs) can be the source of bacteria has been demonstrated (Wisconsin Department of Natural Resources, 1993); therefore, sanitary seals continue to be an issue to consider in well construction.

SUMMARY AND CONCLUSIONS

This study, completed by the USGS, in cooperation with the PaDEP, provides an assessment of the bacteriological quality of untreated ground water from private, household-supply wells in south-central and southeastern Pennsylvania. Water samples were collected from 78 wells in 8 counties (Chester, Cumberland, Dauphin, Lancaster, Lebanon, Montgomery, Perry, and York) from an equal number of sanitary (grouted) and nonsanitary (nongrouted) wells. Sampling took place from September 2000 to March 2001. All samples were collected from wells adjacent to agricultural land-use areas.

Waters from 48 of 78 wells (62 percent) sampled for this study were found to contain total coliform bacteria. *E. coli* bacteria were found in 8 of 78 wells (10 percent). Seventeen percent of the samples that were positive for total coliform also were positive for *E. coli*.

Statistical tests were conducted to determine if the presence of bacteria was related to whether or not grout was installed. Total coliform bacteria were just as likely to be detected in sanitary (grouted) wells as in nonsanitary (nongrouted) wells. However, water from nonsanitary wells was more susceptible to *E. coli* bacteria contamination. *E. coli* bacteria were detected in water from eight household-supply wells sampled; all but two of those wells were nonsanitary wells.

Statistical tests also were conducted to determine if the presence of bacteria was related to bedrock type. The areas underlain by carbonate bedrock had higher percentages of total coliform detected than areas underlain by noncarbonate bedrock but this relation is not statistically significant for total coliform. However, all of the *E. coli* detections were observed in ground water from wells underlain by carbonate bedrock, indicating carbonate aquifers are more vulnerable to *E. coli* bacteria contamination than noncarbonate aquifers.

Statistical tests were done after dividing the data into four groups on the basis of sanitary construction and bedrock type. Comparisons for total coliform do not indicate statistically significant differences among the four groups. On the other hand, 75 percent of the *E. coli* bacteria detected was from water from nonsanitary wells in areas underlain by carbonate bedrock (six of eight wells).

Statistical analyses also were done to determine if the presence of bacteria was related to well-construction characteristics such as well depth, casing length, well age, and depth to the first water-bearing zone. Statistically significant relations are present between the presence of total coliform bacteria and the depth to water-bearing zone in both sanitary and nonsanitary wells in areas underlain by carbonate bedrock. Statistically significant relations also are present between the presence of total coliform bacteria and casing length in nonsanitary wells in areas underlain by noncarbonate bedrock.

Bacteria were found in water samples from wells both with and without insects observed on the underside of the well cap. The data set of wells with sanitary sealed well caps was too small to conduct statistical analyses for this study; therefore, it is uncertain whether installation of sanitary sealed well caps would reduce the incidence of bacteria in ground water from wells.

This study showed a high number of detections of total coliform throughout the study area indicative of the ubiquitous nature of total coliform in the environment (enteric, plant derived, soil derived, and others). Potential pathways for total coliform to enter a well include localized entry from a poorly protected wellhead (no sanitary sealed cap) by pests, particularly earwigs, known to contribute coliform bacteria contamination to ground water. In this scenario, the occurrence of bacteria could be reduced by installing a sanitary sealed well cap. However, because total coliform was detected in a similar number of wells on the basis of sanitary and nonsanitary construction and bedrock type, a combination of characteristics could all be contributing to the bacterial contamination. Aquifer-wide contamination may be likely.

E. coli bacteria is a subset of total coliform bacteria and is not ubiquitous in the environment. Because of this result, fewer detections were observed for *E. coli* than total coliform. Ground water from nonsanitary wells installed in areas underlain by noncarbonate bedrock were most vulnerable to *E. coli* contamination. One possible explanation for the exclusive occurrence of *E. coli* in carbonate aquifers is explained in the following scenario. If the depth to bedrock is shallow in a carbonate system, the capacity of the soil overburden to filter out contaminants would be greatly reduced and the bacteria would have a direct pathway to enter ground water in the well through the porous carbonate bedrock material. Because 75 percent of the *E. coli* detected was in nonsanitary wells, having a well constructed with grout installed along the entire annulus of casing greatly reduces the chance that water from that well will be contaminated with *E. coli* bacteria. One potential pathway for the *E. coli* bacteria to enter water from a nongrouted well would be if the source of contamination is on site—possibly the result of a faulty septic system—and there is a compromised (cracked) casing that could allow a direct path for the bacteria to enter into the well. It also could indicate other localized sources from nearby agricultural operations.

Further study is needed to provide evidence that a well constructed with sanitary features is less likely to contain bacteria. A study designed to revisit wells with bacteria contamination, add a sanitary sealed well cap, sterilize the ground water in the well by chlorination, and resample the water at a later date would help to determine the level of water-source protection afforded by sanitary construction.

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Appendix. *Selected well information and results of bacteria analyses for private household-supply wells in south-central and southeastern Pennsylvania*

[mL, milliliter; <, less than; --, no data; TNTC, too numerous to count]

Site Identifier	Local well number	Date	Time	County	Geology	Sanitary or nonsanitary	Well depth (feet)	Well age (years)	Casing length (feet)	Depth to first water-bearing zone (feet)	Total coliform (colonies per 100 mL)	*E. coli* (colonies per 100 mL)
400846077112501	CU 930	9/27/00	1000	Cumberland	Carbonate	Sanitary	260	1	80	121	10	<1
401616076362501	DA 830	10/04/00	1345	Dauphin	Carbonate	Sanitary	180	5	84	95	1	<1
401901075254801	MG 1811	10/10/00	1105	Montgomery	Noncarbonate	Nonsanitary	140	16	40	90	5	<1
401344075311801	MG 1802	10/10/00	1330	Montgomery	Noncarbonate	Sanitary	147	2	59	--	44	<1
401037077072901	CU 933	10/11/00	930	Cumberland	Carbonate	Sanitary	220	1	83	208	13	<1
394550076100001	LN 2053	10/12/00	1030	Lancaster	Noncarbonate	Nonsanitary	63	22	43	47	2	<1
402337077173801	PE 475	10/16/00	1300	Perry	Carbonate	Sanitary	140	7	81	98	15	<1
400806077073801	CU 932	10/17/00	1535	Cumberland	Carbonate	Sanitary	240	10	200	210	6	<1
401248077064701	CU 935	10/17/00	1200	Cumberland	Carbonate	Sanitary	200	8	--	148	9	<1
400624075443701	CH5992	10/17/00	1330	Chester	Noncarbonate	Sanitary	157	5	40	50	1	<1
401624075344901	MG 1803	10/18/00	1400	Montgomery	Noncarbonate	Sanitary	200	11	100	110	<1	--
400759075421301	CH 5990	10/23/00	1700	Chester	Noncarbonate	Sanitary	180	2	59	70	10	<1
402227075350001	MG 1816	10/23/00	1200	Montgomery	Noncarbonate	Sanitary	250	2	75	135	<1	--
401801075313201	MG 1806	10/23/00	900	Montgomery	Noncarbonate	Sanitary	121	13	44	48	54	<1
400342075515201	CH 5989	10/24/00	1030	Chester	Noncarbonate	Sanitary	180	2	100	120	<1	--
394721076390101	YO 1206	10/25/00	1230	York	Noncarbonate	Nonsanitary	140	16	40	--	<1	--
394343076361301	YO 1207	10/25/00	1600	York	Noncarbonate	Nonsanitary	200	17	42	42	<1	--
395003076110001	LN 2052	10/26/00	900	Lancaster	Noncarbonate	Nonsanitary	180	11	60	80	<1	--
401127077050601	CU 934	10/26/00	1400	Cumberland	Carbonate	Sanitary	160	6	57	60	6	<1
400658075511601	CH 5410	10/30/00	900	Chester	Noncarbonate	Nonsanitary	150	19	51	55	<1	--
400348075552601	CH 5988	10/30/00	1500	Chester	Noncarbonate	Sanitary	120	2	61	75	84	<1
400858075490101	CH 5986	10/30/00	1130	Chester	Noncarbonate	Sanitary	120	2	--	90	2	<1
402054075342301	MG 1818	10/31/00	1245	Montgomery	Noncarbonate	Nonsanitary	200	20	25	65	<1	--
400839075490901	CH 1350	10/31/00	1600	Chester	Noncarbonate	Nonsanitary	66	30	42	58	<1	--
401422075292301	MG 1805	10/31/00	1045	Montgomery	Noncarbonate	Sanitary	247	1	40	--	<1	--
401153075261001	MG 1804	11/2/00	1015	Montgomery	Noncarbonate	Sanitary	180	2	32	60	11	<1
401151075260101	MG 1808	11/2/00	1230	Montgomery	Noncarbonate	Nonsanitary	176	21	40	60	3	<1
400135075542101	CH 4988	11/6/00	900	Chester	Noncarbonate	Nonsanitary	190	23	--	70	<1	--
400034075525001	CH 5987	11/8/00	1530	Chester	Noncarbonate	Sanitary	100	2	37	45	<1	--
400135075300001	MG 1807	11/7/00	1200	Montgomery	Noncarbonate	Nonsanitary	140	18	42.5	90	<1	--

Appendix. *Selected well information and results of bacteria analyses for private household-supply wells in south-central and southeastern Pennsylvania*—*Continued*

[mL, milliliter; <, less than; --, no data; TNTC, too numerous to count]

Site Identifier	Local well number	Date	Time	County	Geology	Sanitary or nonsanitary	Well depth (feet)	Well age (years)	Casing length (feet)	Depth to first water-bearing zone (feet)	Total coliform (colonies per 100 mL)	*E. coli* (colonies per 100 mL)
401734075333101	MG 1817	11/7/00	1000	Montgomery	Noncarbonate	Sanitary	123	11	64.5	70	2	<1
400400075560901	CH 1272	11/14/00	900	Chester	Noncarbonate	Nonsanitary	183	30	30	38	6	<1
401101077072301	CU 936	11/14/00	1150	Cumberland	Carbonate	Nonsanitary	250	9	60	--	<1	--
394759075560301	CH 4933	11/14/00	1200	Chester	Noncarbonate	Nonsanitary	157	25	87	28	<1	--
401829075354501	MG 1813	11/15/00	1530	Montgomery	Noncarbonate	Sanitary	180	4	60	140	<1	--
402145075263201	MG 1809	11/15/00	1200	Montgomery	Noncarbonate	Nonsanitary	240	12	40	178	76	<1
401815075382001	MG 1810	11/15/00	1000	Montgomery	Noncarbonate	Nonsanitary	147	9	80.4	119	8	<1
401727075360801	MG 1812	11/16/00	800	Montgomery	Noncarbonate	Sanitary	123	2	49.2	--	<1	--
400230076410201	YO 1202	11/20/00	1100	York	Noncarbonate	Nonsanitary	140	26	26	65	9	<1
394816076463001	YO 1199	11/20/00	1400	York	Noncarbonate	Nonsanitary	175	23	20.5	71	TNTC	<1
401125077195801	CU 911	11/21/00	1200	Cumberland	Carbonate	Nonsanitary	176	20	108	108	11	<1
400942077041201	CU 919	11/21/00	900	Cumberland	Carbonate	Nonsanitary	165	14	102	102	1	<1
401011077061401	CU 923	11/21/00	1000	Cumberland	Carbonate	Nonsanitary	225	12	80	220	7	<1
401155077001901	CU 942	11/21/00	730	Cumberland	Carbonate	Sanitary	150	9	--	131	15	<1
395752076045001	LN2050	11/27/00	930	Lancaster	Noncarbonate	Nonsanitary	130	22	20	20	27	<1
394426075533501	CH4931	11/27/00	1230	Chester	Noncarbonate	Sanitary	132	9	59	70	1	<1
400515077205501	CU 914	11/29/00	1130	Cumberland	Carbonate	Nonsanitary	147	16	145	139	1	<1
400853077230101	CU 912	11/29/00	1000	Cumberland	Carbonate	Nonsanitary	162	10	120	109	9	<1
400754077195201	CU 913	11/29/00	1500	Cumberland	Carbonate	Nonsanitary	162	11	60	60	<1	--
401136077152701	CU 918	11/30/00	1100	Cumberland	Carbonate	Nonsanitary	203	8	179	198	7	1
400746077262201	CU 910	11/30/00	900	Cumberland	Carbonate	Nonsanitary	198	9	126	126	2	1
400835077171701	CU 916	11/30/00	1330	Cumberland	Carbonate	Nonsanitary	123	21	89	115	7	1
400824077085501	CU 944	12/4/00	1300	Cumberland	Carbonate	Sanitary	100	1	80	90	1	<1
401445076440801	DA 841	12/4/00	1200	Dauphin	Carbonate	Nonsanitary	180	23	40	105	39	4
401750076274601	LB 1164	12/4/00	1000	Lebanon	Carbonate	Nonsanitary	150	13	73	85	TNTC	TNTC
395204076262101	YO 1209	12/4/00	1700	York	Noncarbonate	Sanitary	175	8	52	115	<1	--
400834077134401	CU 917	12/5/00	1100	Cumberland	Carbonate	Nonsanitary	200	12	60	60	<1	--
400103075561801	CH 5991	12/6/00	1400	Chester	Noncarbonate	Sanitary	180	3	126	140	<1	--
401744075312801	MG 1815	12/6/00	1100	Montgomery	Noncarbonate	Sanitary	160	2	63	130	<1	--
401735075293001	MG 1814	12/6/00	1000	Montgomery	Noncarbonate	Sanitary	240	11	240	120	10	<1

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[mL, milliliter; <, less than; --, no data; TNTC, too numerous to count]

Site Identifier	Local well number	Date	Time	County	Geology	Sanitary or nonsanitary	Well depth (feet)	Well age (years)	Casing length (feet)	Depth to first water-bearing zone (feet)	Total coliform (colonies per 100 mL)	*E. coli* (colonies per 100 mL)
394606076002001	CH 4932	12/19/00	1200	Chester	Noncarbonate	Nonsanitary	143	20	52	52	<1	--
401316077023001	CU 946	12/20/00	1000	Cumberland	Carbonate	Sanitary	--	--	--	--	3	1
400854077112701	CU 941	12/20/00	1600	Cumberland	Carbonate	Sanitary	125	2	80	--	23	1
400945077104201	CU 943	12/20/00	1400	Cumberland	Carbonate	Nonsanitary	200	6	20	--	1	1
401111077073001	CU 939	12/21/00	1000	Cumberland	Carbonate	Nonsanitary	150	--	--	--	TNTC	TNTC
400805077074101	CU 940	12/21/00	1200	Cumberland	Carbonate	Sanitary	200	1	80	--	3	<1
400854077161801	CU 937	12/26/00	900	Cumberland	Carbonate	Nonsanitary	200	2	100	--	3	<1
401046077094601	CU 938	12/26/00	1430	Cumberland	Carbonate	Nonsanitary	--	--	--	--	6	<1
401254076114701	LN 2017	1/28/01	900	Lancaster	Noncarbonate	Nonsanitary	160	9	42	105	1	<1
400229076020301	LN 2027	1/29/01	1300	Lancaster	Carbonate	Nonsanitary	175	15	102	102	<1	--
400711076113801	LN 2019	1/29/01	1130	Lancaster	Carbonate	Nonsanitary	200	12	20	176	5	<1
400827077083101	CU 948	1/31/01	900	Cumberland	Carbonate	Sanitary	200	5	57.5	--	<1	--
400238075341301	CH 6398	2/13/01	1030	Chester	Carbonate	Sanitary	--	1	--	--	<1	--
400327075324901	CH 6397	2/13/01	1200	Chester	Carbonate	Sanitary	--	6	--	--	<1	--
405732075541001	CH 5364	2/15/01	1600	Chester	Carbonate	Sanitary	160	3	--	--	<1	--
395747075531301	CH 6179	2/20/01	1000	Chester	Carbonate	Sanitary	--	16	--	--	<1	--
400953077105101	CU 945	3/27/01	1000	Cumberland	Carbonate	Sanitary	180	1	--	--	<1	--
401030077105801	CU 947	3/29/01	910	Cumberland	Carbonate	Sanitary	260	1	100	100	2	<1