The Influence of Well Construction on Bacterial Contamination

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The Influence of Well Construction on Bacterial Contamination

A report by

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INTRODUCTION

In 1990, there were approximately one million private water systems in Pennsylvania that provided water for approximately 3.5 million rural residents who did not have access to a public water supply (U.S. Census Bureau, 1990)[1]. Trends from 1970 to 1990 would suggest that 20,000 new wells are drilled each year, putting the total number of private water systems in Pennsylvania at just over 1.2 million in 2000.

Drilled wells account for over 95 percent of these private water systems, with the remaining 5 percent comprised of hand-dug wells, springs, cisterns, ponds or streams. Unlike community water systems, which are permitted and strictly regulated by the Pennsylvania Department of Environmental Protection (DEP), all aspects of private water system management, including construction, testing and treatment, are the voluntary responsibility of the homeowner. The only national survey of private water systems to date found that the majority failed to meet at least one drinking water standard (Francis et al., 1982). This is a particular rural concern since private wells serve a third of all rural households, compared to 12 percent in urban Pennsylvania.

Bacterial contamination is especially problematic in private wells. There are dozens of types of bacteria that can cause waterborne illnesses, and testing water for all of these bacteria would be both expensive and impractical. Instead, the standard method for determining bacterial safety is a simple and inexpensive total coliform bacteria analysis. The coliform group includes a large number of relatively harmless bacteria; however, a few members of this group are disease-causing organisms. A positive total coliform bacteria test indicates that disease-causing bacteria may be present or that a pathway exists that might allow disease-causing bacteria to contaminate the water supply in the future. State drinking water standards require that community water supplies be free of coliform bacteria but private water systems are not required to meet this standard. Positive total coliform bacteria tests are often followed by more specific tests to determine the source and virulence of the bacteria. For example, testing for E. coli (bacteria that inhabit the lower intestines of warm-blooded animals) can be used to determine if contamination originates from human or animal waste.

Bacterial contamination is one of the most common problems in private water wells in Pennsylvania. The only statewide data, collected in the 1980's, found that 40 percent of private water systems contained coliform bacteria (Sharpe et al., 1985). Some recent regional studies have also documented widespread bacterial contamination of private wells in Pennsylvania:

BACTERIAL CONTAMINATION IS ONE OF THE MOST COMMON PROBLEMS IN PRIVATE WATER WELLS IN PENNSYLVANIA.

- An intensive study of 100 wells in Berks County found that 25 percent of rural home wells and 40 percent of farm wells contained coliform bacteria (Jones, 1989).
- A U.S. Geological Survey (USGS) study of 146 wells in the Lower Susquehanna Valley between 1993 and 1995 found that 70 percent contained coliform bacteria. About 30 percent of an 88-well subset contained E. coli (Bickford et al., 1996).
- A USGS study of 78 wells in south-central and southeastern Pennsylvania from September 2000 to March 2001 found that 62 percent contained total coliform bacteria and 10 percent contained E. coli (Zimmerman et. al., 2001).
- A USGS study of 30 wells in the Delaware River Basin found that 20 percent contained coliform bacteria and 3 percent contained E. coli (Durlin and Schaffstall, 2001).
- A Pennsylvania Department of Agriculture study of private wells in six counties (Bedford, Berks, Blair, Lebanon, Lehigh and Northampton) from 1996 to 1999 found coliform

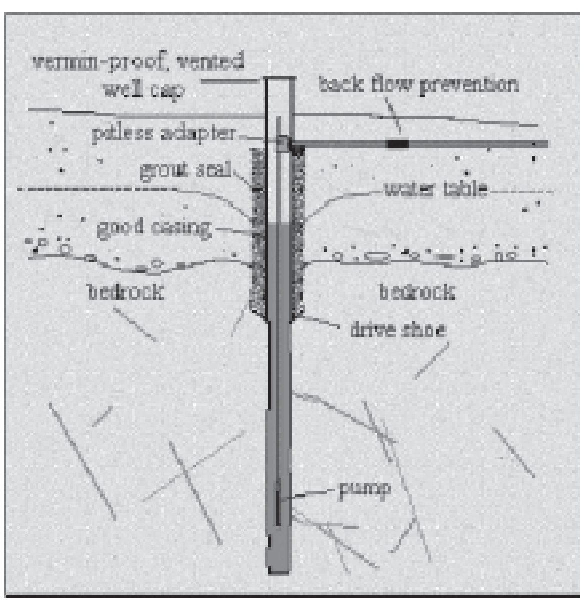
[1] The 2000 Census did not include questions about sources of household water so 1990 is the most recent Census data available.

bacteria in 12 to 86 percent of the wells and *E. coli*. in 0 to 36 percent (written communication in Zimmerman et al., 2001).

A recent USGS study actually identified the occurrence of culturable viruses and *H. pylori* (a pathogenic bacteria) in noncommunity water supply wells in Pennsylvania (Lindsey et al., 2001). These results agree with Craun (1986), who summarized 228 reported outbreaks of waterborne disease affecting more than 27,000 people in the U.S. between 1971 and 1978. He concluded that private water systems and small, semi-public supplies were most vulnerable to waterborne disease. More recent data from Lee et al. (2002) found that 64 percent of the identified waterborne disease outbreaks in the United States during 1999 and 2000 occurred in unregulated private water wells.

Bacterial contamination of ground water wells can occur from both above and below the surface. Large-scale pollution of entire ground water aquifers may occur from failing septic systems or animal wastes, or

Figure 1. Cross-section of a properly constructed or "sanitary" well



Source: Pennsylvania Department of Environmental Protection, 2001

individual wells may be contaminated from the surface near the wellhead. Surface contamination of individual wells is usually caused by surface water flowing along the well casing and/or from a loose fitting or absent well cap that allow insects, animals or surface water to directly enter the well. Jones (1973) provided early evidence of the importance of well construction in preventing bacteria entry into wells.

The type of bedrock around the well is also an important factor in determining its susceptibility to contamination. Carbonate bedrock (limestone and dolomite), which is common in much of central and southeastern Pennsylvania, is typically more fractured and connected to the surface, allowing for rapid movement of groundwater and contaminants over large distances. Noncarbonate bedrock, including shale and sandstone, generally has slower movement of groundwater and less susceptibility to surface contaminants.

By installing a grout seal around the casing and a vermin-proof, or "sanitary," well cap on the top of the well, surface contamination of wells can be prevented. (See Figure 1) A grout seal usually consists of cement or a similar material injected around the well casing to prevent surface water from contaminating the well. A "sanitary" well cap includes a rubber gasket that seals the wellhead from surface water, insects and small mammals. Grout seals and sanitary well caps add costs to the well drilling process. In the absence of regulations, well drillers often construct a "non-sanitary" well with no grout seal and a loose-fitting well cap to be cost-competitive with other drillers.

Pennsylvania is one of only four states that does not have construction standards for private wells. Although the benefits of well construction regulations are theoretically sound, there is a lack of data on the effect of well construction on bacterial contamination.

A recent USGS study took the first steps by comparing bacterial occurrence in 39 "sanitary" wells with a grout seal to 39 "non-sanitary" wells without a grout seal (Zimmerman et al., 2001). Sanitary wells were located in areas with existing well construction ordi-

nances, while non-sanitary wells were located in areas without local regulations. Sixty-two percent of all of the wells contained coliform bacteria and 10 percent also contained *E. coli*. Coliform bacteria contamination was similar between the two groups of wells, but *E. coli* was more likely in non-sanitary wells. “Sanitary” wells in this USGS study had a grout seal, but most had loose fitting rather than sanitary well caps. As a result, insects were frequently observed inside both groups of wells, which could explain the similar coliform bacteria results (Zimmerman et al., 2001). Sanitary well caps are usually not required by local ordinances and are rarely used in Pennsylvania because they are more expensive than standard, loose-fitting well caps.

PROJECT GOALS

Previous studies have documented the prevalence of bacterial contamination in private water wells in Pennsylvania. Serious waterborne illnesses can and do occur as a result of bacterial contamination of wells. Unfortunately, most homeowners are unaware of bacterial contamination, and homeowners that do test their water often purchase expensive water treatment devices. Implementation of construction regulations for new wells and maintenance of existing wells could reduce the prevalence of bacterial contamination. The goal of this project was to determine the reduction of bacterial contamination of both new and existing private water systems through better construction practices.

THE GOAL OF THIS PROJECT WAS TO DETERMINE THE REDUCTION OF BACTERIAL CONTAMINATION OF BOTH NEW AND EXISTING PRIVATE WATER SYSTEMS THROUGH BETTER CONSTRUCTION PRACTICES.

The first step toward this goal was to determine if simple and inexpensive retrofitting and maintenance of existing wells could reduce bacterial contamination and help protect rural residents from waterborne illnesses while providing a less expensive alternative to on-site water treatment.

Second, the research set out to determine if recommended but rarely used well construction practices, including a grout seal and a sanitary well cap, could potentially reduce or eliminate bacterial contamination in new private water wells. Here, the hypothesis was that new wells constructed with a grout seal and a sanitary well cap would rarely contain coliform bacteria.

The ultimate goal of the study was to provide recommendations for policy makers, regulators and homeowners on the proper construction of new and existing wells to minimize bacterial contamination.

This study involved two basic approaches. First, existing wells that were known to contain coliform bacteria were disinfected, fitted with a sanitary well cap, and resampled to determine the effectiveness of retrofitting in eliminating bacterial contamination of existing wells. Second, new wells that were constructed with a grout seal and sanitary well cap were sampled to determine if bacterial contamination rates were generally lower in these wells compared to past surveys of wells with conventional construction. Results from these two studies provided insights and recommendations regarding the importance of well construction in controlling bacterial contamination in both new and existing water wells.

WELL CAPPING STUDY

The well capping study began with 48 wells that contained coliform bacteria when sampled in a recent USGS study in Pennsylvania by Zimmerman et al. (2001). Two additional wells were identified through the Cumberland County Cooperative Extension office providing 50 total wells, thirty-eight of which could be included in the study. The wells were located in southeastern Pennsylvania in Cumberland, Perry, Dauphin, York, Lebanon, Lancaster, Chester and Montgomery counties.

A first collection of water samples from each well took place in February 2002 and followed standard methods recommended by the U.S. Geological Survey (1997). Provisions were made to ensure that samples were collected from the aquifer rather than from water stored in the pressure tank or plumbing system to confirm that sample locations were not influenced by water treatment equipment. Samples were collected and tested for both total coliform and e. coli bacteria.

To ensure data quality, two samples were filtered from each well, including a 100 mL and 200 mL sample. This allowed for comparison of bacteria concentrations between two samples and for more accurate determination of small numbers of bacteria using a larger sample volume (200 mL). Bacteria numbers in each well were computed as the average of the results from the 100 mL and 200 mL samples.

During the February sampling, water samples that tested positive for *E. coli* were tested for five common virulence factors to determine if the *E. coli* strain was potentially harmful to humans. This testing was done to provide some insight into the occurrence of pathogenic bacteria in home water wells.

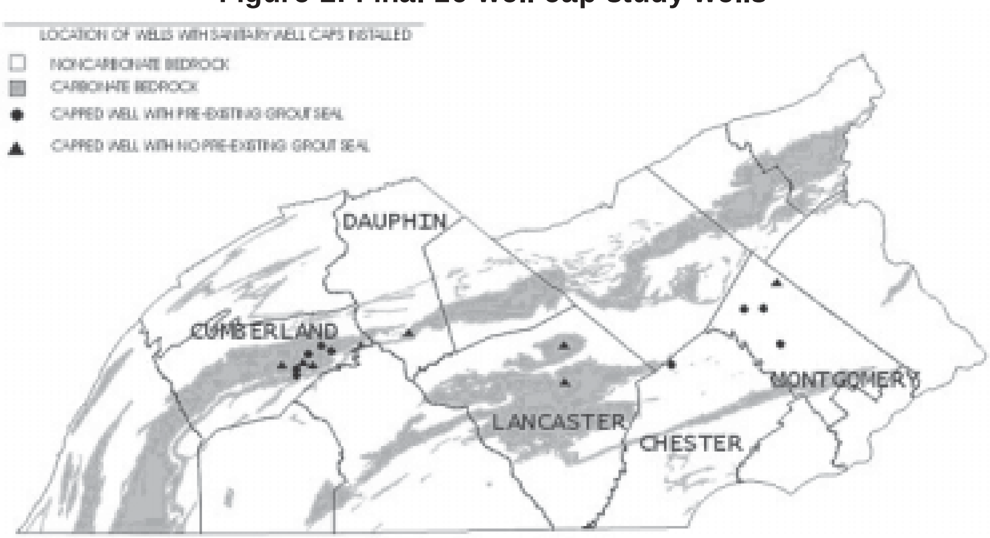
Wells that tested negative for coliform bacteria during February were resampled in May 2002. Wells that did not contain coliform bacteria in February or May were removed from the study. Wells that tested positive were disinfected, fitted with sanitary well caps, and tested again for coliform bacteria in November or December 2002.

Data quality was monitored continuously during the study using frequent sterile blank samples that were known to be free of bacteria because they had been previously sterilized in the lab. Analysis of sterile blanks ensured that there was no inherent contamination of the well samples due to the filtration and incubation processing of samples.

Duplicate analysis of every well during the study (100 and 200 mL filtration) was also a measure of data quality by measuring the repeatability of results. To produce comparable bacteria counts to the 100 mL results, the results from the 200 mL sample were divided by two. This provided a total of 107 duplicate samples. Of these 107 duplicates, 69 produced negative results for both 100 and 200 mL samples. There was no statistical difference between results from filtering 100 and 200 mL in the 38 samples with positive bacteria results. The same was true for *E. coli* results, though the sample size (nine wells) was much smaller.

Although there were no statistical differences between results from 100 and 200 mL samples, there were some indications that 100 mL of sample was not always sufficient to detect small numbers of coliform bacteria. There were eight cases where coliform bacteria were detected in the 200 mL sample but not detected in the 100 mL sample. In each of these cases, the bacteria numbers were small (< 5 colonies) in the 200 mL sample. Still, it is troubling that 20 percent of the wells that tested positive for coliform bacteria were only detected by filtration of 200 mL of sample. Clearly, the standard 100 mL filtration method is not always sufficient to detect coliform bacteria in small numbers. Further study of the standard method for bacteria analysis appears to be warranted especially where bacteria concentrations are low.

Figure 2. Final 16 well cap study wells



Final Site Selection

The sampling of 38 wells in February was meant to confirm the presence of coliform bacteria in these wells before they were disinfected and fitted with sanitary well caps. All of these wells had tested positive for coliform bacteria during 2000-2001 (Zimmerman et al. 2001). Surprisingly, only 14 (37 percent) of the wells tested positive for total coliform bacteria in 2002; 24 tested negative. The 24 negative wells were re-tested during May, when three of the 24 wells tested positive for coliform bacteria. The 21 wells that again tested negative were removed from the study. The 14 wells that tested positive for bacteria during February and the three that were positive in May provided a total of 17 wells that could be disinfected and fitted with a sanitary well cap. One well was removed from the study because the homeowner chose to drill a new well rather than retrofit the existing well. Information on the location of the 16 study wells is shown in Figure 2. Six of the wells were located in non-carbonate bedrock areas while 10 were in carbonate bedrock. Nine of the 16 wells were constructed with a grout seal and seven contained no grout seal around the casing.

Two professional well drillers were contracted to shock chlorinate each well and install a sanitary well cap. Shock chlorination ensured that each well was bacteria-free to properly test the effectiveness of the retrofitted sanitary well cap. This work was completed on each well between June and October 2002. Each homeowner received a fact sheet on shock chlorination in the mail prior to the site visit by the well drillers. The shock chlorination procedure and installation of the sanitary well cap are referred to as "capping" throughout the rest of this report. This study made no attempt to distinguish between the individual effects of shock chlorination and installation of the sanitary well cap since all of the study wells received both treatments.

The 16 wells were re-sampled for bacteria between November 30 and December 4, 2002 to determine the benefit of the capping procedure. The time from the capping to final sample collection was generally 30 to 60 days, and was characterized by precipitation significantly above normal levels. The elapsed time and weather conditions were thought to be sufficient to allow for recontamination of wells impacted by aquifer pollution. Sampling protocols followed those described above.

Results

Table 1 on page 10 shows the characteristics of the 38 study wells and the prevalence of coliform and *E. coli* bacteria in these wells. Coliform bacteria were slightly more common in wells with a grout seal (53 percent) than in wells without a grout seal (38 percent) and more common in wells located in carbonate bedrock (55 percent) than wells in noncarbonate bedrock (33 percent). Wells in carbonate bedrock also tended to have higher numbers of coliform bacteria. These results agree with data from Zimmerman et al. (2001) on these wells and 40 other wells in southeastern Pennsylvania.

The disappearance of coliform bacteria from 21 of the original 38 wells between the 2000 and 2001 USGS sampling and the sampling in early 2002 was somewhat surprising. Temporal variability in coliform bacteria numbers in wells has been reported in some studies (Jones, 1973; Oliphant et al., 2002). The presence of an extreme drought in the region from October 2001 through February 2002 (the initial sampling date) may explain the observed results.[2] The counties where the study wells were located were all under a Drought Emergency during February 2002, primarily due to extremely low groundwater levels. Groundwater levels

[2] Since coliform bacteria are surface organisms, they are more likely to be carried into groundwater during periods of rapid groundwater recharge by surface water. During periods of drought, the lack of groundwater recharge could reduce bacterial contamination of wells by removing the source of the bacteria (surface water contamination) or by reducing the movement of underground contamination sources (i.e.: less movement of septic systems effluent). The lack of precipitation during the fall and winter had effectively prevented groundwater recharge in these wells for several months.

Table 1. Results of initial bacteria testing on 38 private water wells, February and May 2002

Type of Well	Number of Wells	Number of Wells with Coliform Bacteria	Number of Wells with *E. coli* bacteria
Carbonate / No Grout Seal	13	6	3
Carbonate / Grout Seal	7	5	1
Noncarbonate / No Grout Seal	8	2	0
Noncarbonate / Grout Seal	10	4	0
Total	30	17	4

in some county monitoring wells in southeastern Pennsylvania were at the lowest levels ever observed.

Four of the 38 wells (11 percent) contained *E. coli* bacteria during the February/May sampling. This was similar to the 10 percent that contained *E. coli* during 2000 and 2001. Since *E. coli* bacteria can only originate from human or animal wastes, these wells represent more serious contamination problems. All four of the wells that contained *E. coli* were found in carbonate bedrock, and three of the four wells did not have a grout seal. These results also agree with the previous results by Zimmerman et al. (2001).

Analysis of six *E. coli* colonies from four wells by the Penn State Gastroenteric Disease Center identified one colony in one well that was potentially virulent. This "serotyping" analysis tested for five common virulence factors related to *E. coli*. These tests targeted the most common disease-causing strains but did not completely eliminate the possibility that other *E. coli* could be virulent.

Effects of Sanitary Well Cap Installation

After shock chlorination and installation of sanitary well caps on the 16 study wells, water samples were collected to determine the effect of these measures on preventing re-contamination of these wells. Of the 16 capped wells, nine were still contaminated with coliform bacteria after shock chlorination and installation of the sanitary cap, while seven did not contain coliform bacteria. Although four of the wells contained *E. coli* before they were capped, none of the wells tested positive for *E. coli* after capping. Table 2 relates the occurrence of coliform bacteria in the capped wells to well characteristics.

Of the 16 wells that were capped, those in carbonate bedrock were only slightly more likely to have bacteria return compared to wells in non-carbonate bedrock. The capping procedure was much more successful on wells that had small numbers of bacteria compared to those that had more gross contamination. Of the 10 wells that had only one or two coliform bacteria colonies before capping, only three still had bacteria after capping. On the other hand, all six of the wells with three or more coliform bacteria colonies before capping still had bacteria after capping. The wells where capping was successful had higher coliform bacteria concentrations (up to 13 colonies per 100 mL) during 2000 and 2001, suggesting that capping can also be successful on wells where bacteria levels are intermittently higher.

Of the 16 capped wells, nine had a pre-existing grout seal. The remaining seven wells did not have an existing grout seal – the predominant type of private well in Pennsylvania. Five of the seven (71 percent) wells without a grout seal were still contaminated with coliform bacteria after capping. Since these wells did not have an existing grout seal, the return of contamination could be due to large-scale aquifer contamination or simply due to surface water contamination around the casing. The two wells without a grout seal that were successfully treated by capping had smaller numbers of bacteria prior to capping. Only four of the nine (44 percent) wells with a pre-existing grout seal still contained coliform bacteria after capping, but three of these wells were also located in carbonate bedrock. The cumulative impact of a grout seal and sanitary well cap was more easily measured by sampling newly constructed wells with these characteristics.

Table 2. Coliform presence in the capped wells

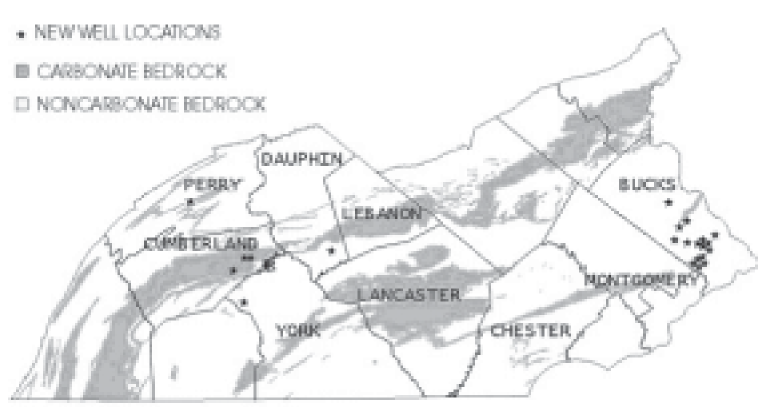
	Wells with No Grout Seal/Wells with Coliform Present	Wells with Existing Grout Seal/Wells with Coliform Present)	Total Wells/Total Wells with Coliform Present
Carbonate Bedrock	5/3	5/3	10/6
Noncarbonate Bedrock	2/2	4/1	6/3
Total	7/5	9/4	16/9

NEW WELL STUDY

New wells constructed with a grout seal and sanitary well cap were not required in Pennsylvania at the time of the study except by a few local ordinances. Project personnel searched well drilling records from two major well drillers in southeastern Pennsylvania for new private, residential wells constructed with a grout seal and sanitary well cap. A total of 24 new wells, illustrated in Figure 3, were identified in the following counties: Bucks (16), Cumberland (5), Dauphin (1), York (1), and Perry (1). These wells were generally drilled within two years of the study, although a few had been drilled up to 10 years prior. Eighteen of these wells were located in non-carbonate bedrock, while six were located in carbonate bedrock.

Water samples were collected between November 9 and December 4, 2002 at outside taps where water treatment equipment was absent or could be bypassed and at the pressure tank from the few homes where water treatment equipment existed and could not be bypassed. Sample collection and analyses followed the same protocols as in the well capping study.

Figure 3. Twenty-four new well study wells



Results

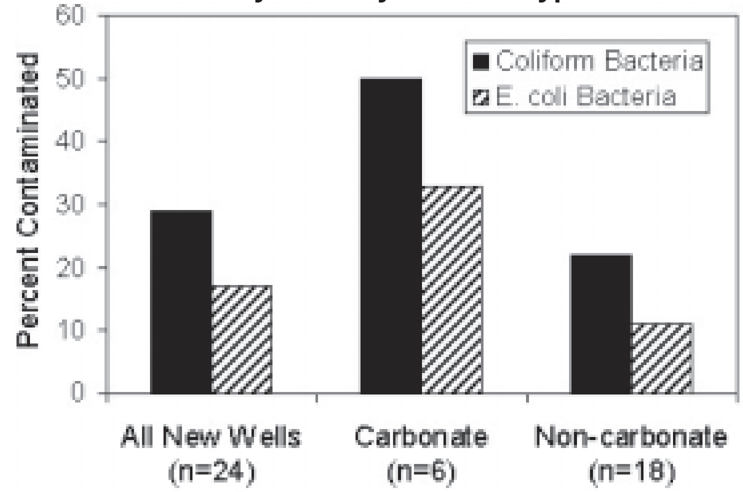
Sampling of 24 new wells constructed with a grout seal and sanitary well cap was completed from November 30 to December 4, 2002. As seen in Figure 4, contamination rates were relatively low among the new wells, with 29 percent containing coliform bacteria and 18 percent containing *E. coli*. Contamination rates for both coliform and *E. coli* bacteria were higher for new wells constructed in carbonate bedrock, although the sample size is small (n=6). The percentage of new wells in carbonate bedrock that tested positive for coliform bacteria was similar to the percentage of capped wells in carbonate bedrock that still contained coliform bacteria after capping. Still, these percentages were both far below the occurrence of coliform bacteria in nonsanitary wells in carbonate bedrock reported by Zimmerman et al. (2001).

Contamination rates were very low (22 percent) for new wells in noncarbonate bedrock. Of the four wells in noncarbonate bedrock that were contaminated, two were within 200 yards of each other and were both grossly contaminated with both coliform and *E. coli* bacteria. These two wells were apparently affected by aquifer contamination from local agricultural or septic system sources.

Costs Associated with Sanitary Well Construction

Results from these studies have implications for the retrofitting of existing wells in addition to construction of new water wells. Homeowners with existing wells that test positive for total coliform bacteria may be interested in disinfecting their wells and retrofitting them, with a sanitary well cap. Disinfection can be accomplished easily by

Figure 4. Coliform and *E. coli* bacterial contamination of study wells by bedrock type



the homeowner using standard chlorine bleach for less than $5. Penn State Cooperative Extension offers a fact sheet that describes how to disinfect an existing well. Sanitary well caps are generally available for $40 to $50 from local well drillers. While homeowners can easily install wells, this study used professional well drillers. The average cost per well for disinfection and installation of a sanitary well cap by a professional well driller in this study was $100.

The installation of a grout seal can also be included on new well construction. It is usually not possible or advisable to install or retrofit a grout seal on an existing well. The cost associated with a grout seal is more difficult to generalize. Grout is usually installed by pumping it into the well from the bottom of the casing until it appears at the ground surface. The length of casing (i.e. depth to bedrock) and the presence of underground voids that consume the grout can affect cost. In general, grouting will add approximately $300 to $500 to the cost of drilling a new well. Higher costs would be more common in limestone areas where underground voids are frequently encountered.

CONCLUSIONS

Data from this study suggest that well construction practices influence bacterial contamination of private wells, but significant bacterial contamination of wells can be expected even in properly constructed wells. Detailed conclusions were hampered somewhat by the small number of wells available for the study due to extreme drought conditions, and the difficulty in locating new wells with sanitary construction. Despite these limitations, some important conclusions can be drawn from the results including:

• Shock chlorination and the installation of a sanitary well cap were effective in removing coliform bacteria from some wells, especially those that originally contained low numbers of coliform bacteria and no *E. coli* bacteria. Shock chlorination and installation of a sanitary well cap were also more successful on wells that already had a grout seal suggesting an additive benefit of sanitary well construction characteristics. Small sample sizes prevented robust comparisons of the effectiveness of this treatment on different types of existing wells. The effects of well capping demonstrated here might be conservative, since all of the study wells were selected during an extreme drought. In this respect, the pool of study wells may be skewed toward wells that are impacted by more serious bacterial contamination.

• Although bacteria were successfully removed from nine of the 16 capped wells for several months, the long-term effect on these wells is unknown. A study of six wells containing coliform bacteria by Oliphant et al. (2002) found that bacteria generally returned to wells very quickly after disinfection but occasionally took up to 21 weeks to reappear. Further sampling of the capped wells would be necessary to determine the long-term benefit of disinfection and sanitary well cap installation.

• Aquifer contamination is a significant source of bacterial contamination in private wells. This is evidenced by the fact that both new and retrofitted wells with sanitary construction (grout seal and sanitary well cap) still had contamination rates of 29 to 44 percent. Wells influenced by aquifer contamination cannot be addressed with improved well construction practices alone.

• A grout seal alone did not reduce coliform bacteria contamination but did reduce *E. coli* contamination. This conclusion is based on past sampling by

Zimmerman et al. (2001) and the limited initial sampling in this study of 38 wells with and without a grout seal. The ability of a grout seal to reduce *E. coli* bacteria is significant, since *E. coli* constitutes a much higher threat of disease than coliform bacteria alone. In this study, shock chlorination and installation of a sanitary well cap eliminated *E. coli* from the four wells that had previously tested positive.

• Bacterial concentrations in wells vary considerably over time, perhaps responding to climatic or seasonal variations. More research is needed to better quantify these variations.

• Wells in carbonate bedrock areas were more likely to contain coliform bacteria and *E. coli* bacteria than wells in noncarbonate bedrock regardless of well construction, suggesting that aquifer contamination is more prevalent in carbonate aquifers. New and existing wells constructed in noncarbonate bedrock had very low bacterial contamination rates.

• Drinking water standards for public water supplies use a coliform bacteria method of filtering 100 mL of sample and may not adequately detect small numbers of bacteria in household supply wells. More research may be needed on this methodology to determine the optimum sample volume.

• Results from this study provide important previously unavailable data on the impact of some well construction practices on bacterial contamination. The wells included in this study were carefully selected to represent both existing and new wells from the two major types of bedrock in Pennsylvania. Intensive research studies on private water wells typically choose to work with small numbers of carefully selected wells due to logistical problems inherent with working with homeowners and the travel costs associated with spatially representative samples. The pool of potential study wells was further restricted for this study because new wells with sanitary construction are rare in Pennsylvania. In areas where recent local ordinances now require sanitary well construction, more potential wells will become available for future study of the impact of well construction practices on water quality.

RECOMMENDATIONS

The typical drilled well in Pennsylvania does not have a grout seal or a sanitary well cap. Results from this study warrant recommending shock chlorination and retrofitting of existing wells with a sanitary well cap for homeowners with wells contaminated with coliform bacteria. This is especially true for homeowners with wells that have small numbers of coliform bacteria and no *E. coli* bacteria and wells located in noncarbonate bedrock where aquifer contamination is less likely. Retrofitting existing wells with a grout seal is usually not feasible, and the benefits are questionable.

Results from this study also have implications for policy makers regarding the construction of about 20,000 new water wells each year in Pennsylvania. These results, along with past studies, provide a framework for specific well construction characteristics and their expected benefits to groundwater quality. Regulations are recommended that require new wells to be constructed with a sanitary well cap as well as shock chlorination following completion of the well. It is also recommended that regulations require existing wells to be retrofitted with a sanitary well cap upon the completion of well maintenance or repairs, including installation of new submersible pumps, well redevelopment or drilling.

This research and past studies support the requirement of a grout seal on new well construction to reduce *E. coli* contamination of wells. More research is needed to determine the effect of different grout methods and materials on bacterial contamination in wells.

There is a need for more research on bacterial contamination of wells in relation to land use, human activities, bedrock types, and well construction. This would require a much larger study of many more wells in differing settings across Pennsylvania. Further monitoring of the 16 capped wells would be helpful to determine the long-term impact of disinfection and sanitary well cap retrofitting of existing wells.

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