Assessing the Well Water Quality in a Rural Georgia County:
Do Washington County Citizens Need to Worry?

by
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Abstract

Under the Safe Drinking Water Act, public water sources must be monitored for contaminants; and the results are made public. However, this Act does not cover private wells, leaving a significant portion of the population unprotected. In one rural Georgia county, Washington, an estimated 3,997 wells are currently in use. Local health officials believe that well contamination is a problem for the people using these wells. The purpose of this project was to take the available data and briefly assess the state-of-affairs for the county. After researching topics unique to Washington County and determining potential sources of well water contamination, aluminum, silica, manganese, total and fecal coliform bacteria, pH, and hardness were chosen for assessment. Despite limitations in the data, this study filled an important knowledge gap for Washington County in that no analysis had been conducted of the available data. For the parameters tested, it was concluded that Washington County well owners were not facing a significant health threat. Additionally, differences in contaminant levels among soil type and year of sample were not significant. The most important problem currently facing the county is lack of data. Washington County must begin to test wells more frequently to better assess contaminants of concern and to focus education and remediation efforts.

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Introduction

What makes well contamination an important public health issue?

Under the Safe Drinking Water Act (SDWA), the safety of water supplied to many Americans is monitored. Amendments passed in 1996 to this federal law even force public water suppliers to publish detailed accounts of water quality. This law increases the safety of drinking water for the approximately 225 million Americans on public water systems. However, it also leaves a significant portion of the population without protection. An estimated 40 to 45 million Americans receive their water supply from private wells which are not monitored under the SDWA (Focazio 2006, Wojcik 1996). Analysis of water from some of these wells reveals presence of contaminants including nitrates, volatile organic compounds (VOCs), heavy metals, bacteria, and others.

These contaminants pose potential human health risks. Common sources of nitrates include agricultural runoff and animal and human wastes, and a common health concern associated with them is methemoglobinemia, or "blue baby syndrome." This condition inhibits the ability of hemoglobin in red blood cells to bind oxygen; and, if extensive, can prove fatal (Benson 2006, Mitchell 1996). VOCs often come from industrial sources such as solvents and petroleum products. They can either degrade quickly or persist for prolonged periods and have both acute and chronic health effects. Tricholoroethylene, one VOC example, can cause irritation of the eyes, nose, and throat, central nervous system disorders, and depression (Aelion 2004, Focazio 2006, Logue 1985). Manganese, a metal found commonly in drinking water, is an essential trace element in the human diet; however, at high levels, it can cause impairments in motor skills and cognitive disorders. Bacteria may be introduced into the well by sewage effluent, agricultural runoff, and animal waste. While most bacteria pose no significant health threat, some, in particular fecal bacteria, can cause gastrointestinal illnesses. *Shigella*, for instance, can cause bacillary dysentery, an infectious disease of the intestinal tract which causes fever, abdominal pain, and diarrhea (Every 1995). Other water quality concerns such as pH and high levels of silica, while not posing a health concern, cause problems for homeowners in other ways such as plumbing pipe scaling, corrosion, and foul odor in the water.

Even though the public and private drinking water supplies in the United States are relatively safe, several studies have shown elevated levels of some of these contaminants in private wells. A USGS study found elevated levels of VOCs in 65% of wells tested while 1% of wells had levels higher than the maximum contaminant level (MCL) set by the EPA for VOCs (Rowe 2007). In a study of 70 wells in rural South Carolina, elevated VOCs were detected in 11; and elevated nitrates were detected in 20 (Aelion 2004). Many other studies have reported elevated coliform bacteria, pesticides, VOCs, radionuclides, arsenic, and other contaminants (Borchardt 2004, Focazio 2006, George 2006, Mitchell 1996, Shaw, 2005, Swistock 2005, Tuthill 1998). These studies are not without their limitations, however.

For example, sampling in the South Carolina study was nonrandom. Random sampling ensures greater statistical validity. It also ensures that the results can be generalized to a greater population. However, in that study participants were chosen based on their proximity to a Toxic Release Inventory site registered for VOCs. While this study could prove useful in determining whether significant leaching from the toxic waste site occurs, the approach potentially biases the study towards finding VOCs. Another limitation of these types of exposure studies is recall bias. If residents must answer question related to their actual daily intake of well water, they may not be able to recall precise intakes and their exposure may be either over- or underestimated. Despite the limitations of these studies, they illustrate the ubiquitous nature of well contamination. Additionally, approximately 15% of the population of the United States is served by private wells with over 90,000 added each year (Focazio 2006). A potential public health concern which reaches so many people and one that can be mitigated in many circumstances should not be ignored.

Because testing of these wells is not required, however, many well owners may not be aware of potential health or structural risks associated with their drinking water. This segment of the population can, therefore, benefit from efforts such as localized surveys of water quality and public outreach education. In most areas, county residents can visit their health department or county extension office for well water testing. However, the tests are not free, which prohibits poorer residents from accessing these services. Additionally, county workers do not regularly visit homes unless they are called by the residents, which can prevent some residents from being aware of the services. If water quality problems exist and are identified, many options such as disinfection and filtration are available and may prove effective in reducing risk.

What unique well water quality issues does Washington County face?

The available literature makes a good argument that poor water quality is a concern to rural residents in the United States; however, these generalized conclusions cannot be applied to each area of the country. Therefore, it is important to examine specific issues facing rural communities, like Washington County, Georgia, where contaminated wells pose a potential health threat to its residents. This county, located in east central Georgia (Figure 1), is home to approximately 21,176 citizens and remains rural with a significant fraction of the population receiving their drinking water from private wells. Local health officials cite poor water quality as a major concern for the county (Smith 2008, Law 2008).

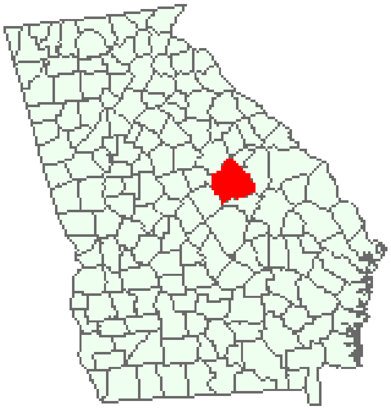


Figure 1. Washington County is highlighted in red. This picture was downloaded. (USEPAc)

According to Sidney Law, the county's University of Georgia extension agent, this topic is extremely important because "I believe we have more contaminated well water than anyone realizes." His office tests for the presence of chemicals and minerals. Jason Smith, with the Public Health Department, also believes well water quality can be improved in the county. His office provides total and fecal coliform bacteria testing. Both of these officials agree that old and improperly constructed wells and septic systems in disrepair cause some of the water quality problems.

Although the wells are only tested upon homeowners' requests, the quality of the surface water and ground water has been tested, in compliance with the SDWA, and both have been found to be impaired in the area. The EPA lists 27 of the water bodies in the three watersheds converging in Washington County, the Ohoopee, the Lower Oconee, and the Upper Ogeechee, as impaired; 7 of them are impaired because they contain high levels of fecal coliform bacteria (US EPA 2005, 2007b&c). Additionally, the EPA listed the water supply for one of the cities in the county, Tennille, as impaired by 1,1-dichloroethylene (DCE). DCE is a VOC that does not occur naturally. Instead it is introduced into the environment by industry; it is used to make plastics and textiles. Additionally, TCE can be reduced to DCE in the environment (Fishbein 1979, Schwarzenbach 2003). From July 1, 2005, to September 30, 2005, the level in the water supply was 7.325 ppb, just above the MCL of 7 ppb (USEPA 2007a). These data support the officials' concerns about the county's water quality. Due to the presence of fecal bacteria and DCE in the surface and ground waters in the county, private wells have the potential to be contaminated also.

Other potential exposure routes exist in the county and provide further evidence for concern about the quality of well water. Because it is still a largely rural county, many family farms exist within its borders. The run-off from these farms combined with old or improperly constructed wells could introduce bacteria and nitrates into well water, such as has been reported in other farming areas (Swistock 2005). In Washington County, for example, health officials have found contaminated wells that were located in cow pastures (Smith 2008). Additionally, failing septic systems can introduce bacteria into wells (Swistock 2005, Tuthill 1998).

In addition to farm animal rearing, a kaolin industry is present in Washington County. The kaolin industry is a potential source of minerals in well water. Kaolin was formed in this county because it is located on Georgia's Fall Line, a geological feature separating the Piedmont from the Coastal Plains. The Fall Line represents the ancient sea level. For this reason many marine fossils were deposited there, and overtime they formed kaolin deposits. Kaolin mining is the major industry in Washington County, which is known as the Kaolin Capital of the World. Because it is a natural part of the geology of the county and because mining practices disturb the natural deposits introducing them into the air, minerals such as aluminum and silica, part of its composition, are of particular concern to well owners. Being used in products such as powdered detergents, gloss coating for paper, china, and kaopectates, its chemical composition is $Al_2Si_2O_5(OH)_4$.

Although generally believed to pose little harm to humans or the environment, the mining practices clearly disturb the natural deposits and, therefore, cause concern for introduction into the waterways and wells. Kaolin is extracted via large, open pit mines. While the companies do employ measure such as wet mining to reduce dust being introduced into the air, the presence of kaolin dust is noticeable, particularly along roads located near mines. The roads, trees, and cars become coated with the white dust characteristic of kaolin. Since this dust persists visibly, the potential for the minerals being washed into wells via runoff exists; and, if surface waters contain kaolin, these may enter aquifers posing threat to well water supplies.

Importance to the County

The importance of well water quality to citizens in rural America is evident. Studies have shown that they can be contaminated with many substances like bacteria and chemicals. However, each area faces unique problems. In Washington County, public health officials believe that well water quality is an important issue; and between the farms and kaolin industry, sources of contamination exist. This project examines data available within the county to make a preliminary determination of contaminants of concern. Bacteria and three minerals, silica, aluminum, and manganese were chosen to explore. This project will attempt to determine whether these substances pose a health hazard or nuisance to the citizens of the county.

Materials and Methods

Mineral Data

Sidney Law with the University of Georgia Extension office provided all available mineral tests conducted from 2002 to 2008. Upon homeowner's request, his office collected a water sample from the home and submitted same to the Soil, Plant, and Water laboratory at the University of Georgia, for testing. Analysis included the following components: pH, hardness, aluminum, boron, cadmium, calcium, chromium, copper, iron, magnesium, manganese, molybdenum, nickel, phosphorus, potassium, sodium, and zinc. Additional tests for substances such as pesticides may be provided at extra cost to the homeowner. These, however, were not requested frequently and thus were not included in this report.

A total of 46 reports were provided. One was excluded from analysis because it was from an irrigation well and not from a household well. Three reports were excluded because they represented duplicate samples sent to a different laboratory presumably for quality control. Two other reports were excluded because they did not contain values for all of the minerals chosen for analysis. The final sample set of mineral data from the extension office consisted of 40 household wells.

Due to privacy concerns, all personal information was deleted from the files by employees at the extension office. However, the approximate location of each well was included and was circled on a Georgia Department of Transportation (GDOT) map. Using the General Soil Map for Washington County (USDA 1985), each well was matched to its corresponding soil type. Using best judgment in comparing the location indicated on the GDOT map to the soil map, the soil type for each well was determined and used for statistical analysis. It is important to note that this lack of precision in the soil type date represents a major limitation in this study because the wells might not be accurately matched to the correct soil type. In the soil survey of the county, soil maps more precise than the General Soil Map are provided. Additionally, the actual location of the well might be misjudged. Therefore, any statistical analysis of correlations between contaminant level and soil type could be inaccurate. The soil types provided by the General Soil Map and their descriptions are presented in Table 1.

Soil Classifications in Washington County		
	Soil Classification	**Description**
1	Chewacla-Chastain-Congaree	Nearly level, poorly drained to well drained soils that have a loamy surface layer and a loamy or clayey subsoil or underlying layers
2	Bibb-Kinston	Nearly level, poorly drained soils that have a loamy or sandy surface layer and loamy or sandy underlying layers
3	Ardilla-Persanti-Ocilla	Nearly level, somewhat poorly drained and moderately well drained soils that have a sandy or loamy surface layer and a loamy or clayey subsoil
4	Orangeburg-Faceville-Greenville	Nearly level to sloping, well drained soils that have a sandy or loamy surface layer and a loamy or clayey subsoil
5	Fuquay-Lakeland-Dothan	Nearly level to sloping, well drained and excessively drained soils that have a sandy surface layer and a loamy subsoil or sandy underlying layers
6	Dothan-Tifton-Faceville	Nearly level to gently sloping, well drained soils that have a sandy or loamy surface layer and a loamy or clayey subsoil that commonly is 5 percent or more plinthite
7	Cowarts-Nankin-Dothan	Nearly level to sloping, well drained soils that have a sandy or loamy surface layer and a loamy or clayey subsoil
8	Lakeland-Eustis	Nearly level to sloping, excessively drained and somewhat excessively drained soils that are sandy throughout
9	Udorthents-Pitts	Gently sloping to moderately steep disturbed soil material and pits in areas that were mined for kaolin
10	Vaucluse-Ailey-Cowarts	Very gently sloping to moderately steep, well drained soils that have a sandy or loamy surface layer and a loamy subsoil
11	Lakeland-Lucy-Orangeburg	Nearly level to moderately steep, excessively drained and well drained soils that have a sandy or loamy surface layer and a loamy subsoil or sandy underlying layers
12	Orangeburg	Sloping and moderately steep, well drained soils that have a sandy or loamy surface layer and a loamy subsoil

Table 1. Quoted from the General Soil Map (USDA).

To make a brief assessment of water quality for the county, the following three minerals were chosen from the reports for analysis: aluminum (Al), silicon dioxide also known as silica (SiO_2), and manganese (Mn). Rationale for inclusion in the study- aluminum and silicon dioxide (SiO_2) were chosen because they are part of the chemical composition of kaolin, also called aluminum silicate, $Al_2Si_2O_5(OH)_4$. Kaolin is mined actively and kaolin dust covers some roads in the county and could enter wells via run-off. Wells located close to active kaolin mines would be particularly susceptible. The EPA has established a secondary drinking water standard of 0.2 ppm for Al. Secondary standards are established for contaminants that are not considered health threats but can cause nuisances. Al can cause color in the water. The EPA has not set a drinking water standard for SiO_2. However, it can cause scaling in pipes. Manganese was chosen for analysis to provide another example of a regulated mineral. The EPA has established a secondary drinking water standard of 2.0 ppm because it is not considered a threat to human health. Mn is an essential trace element in the human diet. However, it can cause impairments in motor skills and cognitive disorders at high levels.

Bacteriological Data

Jason Smith, director of public health, Washington County Health Department, provided the bacteriological tests conducted by that Health Department from 2002 to 2008. The Department tests well water for total and fecal coliform bacteria upon homeowner's request. Tests for 150 wells were provided. Because only a few follow-up samples were conducted, no temporal comparisons could be made. Therefore, only the first sample was included in the present report. Some of the tests were performed for businesses. These tests were excluded ensuring that only household wells were analyzed. The final data set consisted of data from 132 individual household wells.

All names and addresses were removed from the data to maintain homeowner privacy. Unlike the earlier data from the Extension Office, however, the general location of the well was not provided by the Washington County Health Department. Therefore, bacteriological data was not classified by soil type. It was also not possible to make correlations between pH, hardness, mineral, and bacterial levels. The mineral and bacteriological tests were requested separately and no coordinating database exists between the Extension Office and the Washington County Health Department. Additionally, because names and addresses were removed by the agencies, mineral data and bacteriological reports could not be matched. The wells were tested for total and fecal coliform bacteria. In most cases, the results of both tests were provided. However, if only total coliform bacteria data were provided and it was negative, it was assumed that fecal coliform was also negative. Table 2 shows the three possible categories of bacteriological data.

Results of Bacteriological Tests	
Total Coliform	**Fecal Coliform**
Negative	Negative
Positive	Positive
Positive	Negative

Table 2. Possible results of the bacteriological tests.

County Wells

Because the county does not require homeowners to register for permits before digging a personal well, the total number of wells in the county is not known. In fact very few records related to household wells were kept before 2003 (personal communication, Jason Smith 2008). The Washington County Health Department does not require but recommends testing of new wells. It is, therefore, difficult to accurately determine the total number of household wells within Washington County. Well drillers, however, file an intent-to-drill with the Health Department. These forms include a description of the type and size of well, intended depth, and infrequently provide a soil profile of the site (Smith 2008). The Health Department was able to provide all available intent-to-drill notices from 2001 to 2008.

To approximate the total number of household wells in the county, the 2000 census data and intent-to-drill notices were used. The total number of households within the cities of Washington County was subtracted from the total number of households in the county. The total number of intent–to-drill notices was added to this count to obtain an approximate number of the total household wells located within the county in 2008. This count may not accurately reflect the total number of wells because of the following assumptions: all houses were included in the 2000 census; these houses only have one private well each, an intent-to-drill form was completed for all new wells dug between 2001 and 2008, and these wells were dug for new houses and not to replace dry wells at existing houses.

Analysis of Data

All statistical analysis was performed in R. R is an open-source software package downloaded at www.r-project.org. It is often used for statistical analysis (Verzani 2005). The percentage of the total number of wells in the county that were actually tested for coliform bacteria or mineral concentration was calculated. The total number and percentage of wells that tested positive for total and fecal coliform bacteria was determined. Average pH and hardness were calculated. From the mineral reports, the total number and percentage of wells that had levels higher than the drinking water standard established by the EPA were determined for each of the three minerals chosen for analysis. Additionally, from the mineral reports, an analysis of variance was performed to determine statistically different levels, if present, of minerals, pH, and hardness among the different soil types. Excluding bacteria data, all data was log-transformed to approximate a normal distribution.

Al and Mn levels were often negligible, being below detection limits for those minerals. It is difficult to analyze this type of censored data because the exact values of those data points are not known and the true mean and standard deviation must be approximated. In such cases, the expected maximization, or EM, algorithm was used. This is an iterative process that fills in the missing values and updates the population estimates until the calculated means and standard deviations no longer differ. By applying an EM algorithm to Al and Mn data, it was possible to best approximate the true mean and standard deviation of the population.

Results and Discussion

County Wells

According to the 2000 United States Census, Washington County had 21,176 residents living in 8327 housing units. The following table shows the breakdown by city.

Washington County Population by City		
City	**Population**	**Housing Units**
Davisboro	1544	158
Deepstep	1544	59
Harrison	509	210
Oconee	280	102
Riddleville	124	46
Tennille	1505	683
Sandersville	6144	2589
Warthen	1418	631
Total	11,656	4478

Table 3. These data were obtained from the 2000 U.S. Census.

Therefore, the population living outside the city limits was 9520. They lived in 3849 housing units. Assuming that everyone housed within the city limits accessed the public water system and that each household only had one well, 3849 wells were in use in the county in 2000. They provided water to 45% of the population. Between 2001 and 2008, 148 drilling permits were filed with the Washington County Health Department. Assuming that these permits represented requests to put in new wells at newly constructed houses, the total numbers of wells in use in the county in 2008 was 3,997. Due to the assumptions made, this number might underestimate the actual well count in the county. If any resident living within city limits chooses to operate a well, they are not represented. Multiple wells at households are not considered. The number of permits on file might not represent the total number of new wells dug.

Another limitation of this count is that it cannot account for older, abandoned wells that have not been filled in, such as old hand dug wells and old bore wells with the pump removed. These wells pose a hazard to the county not only if children fall in but also if they are located close to the wells in use. They represent an open access point into the water supply. Any runoff that enters them could contaminate the ground water and increase the likelihood of having poor water quality from the bore well currently in use.

Despite the limitations of this well count, it is clear that only a small number of well owners chose to have their water tested. The following table shows the total number of mineral and bacteria tests performed and the percentages they represent.

Well Tests Performed in Washington County		
Test	**Number of Wells Tested**	**Percentage of Total County Wells Tested**
Mineral	40	1%
Bacteria	132	3.3%
Total	172	4.3%

Table 4. Total number and percentages of wells tested.

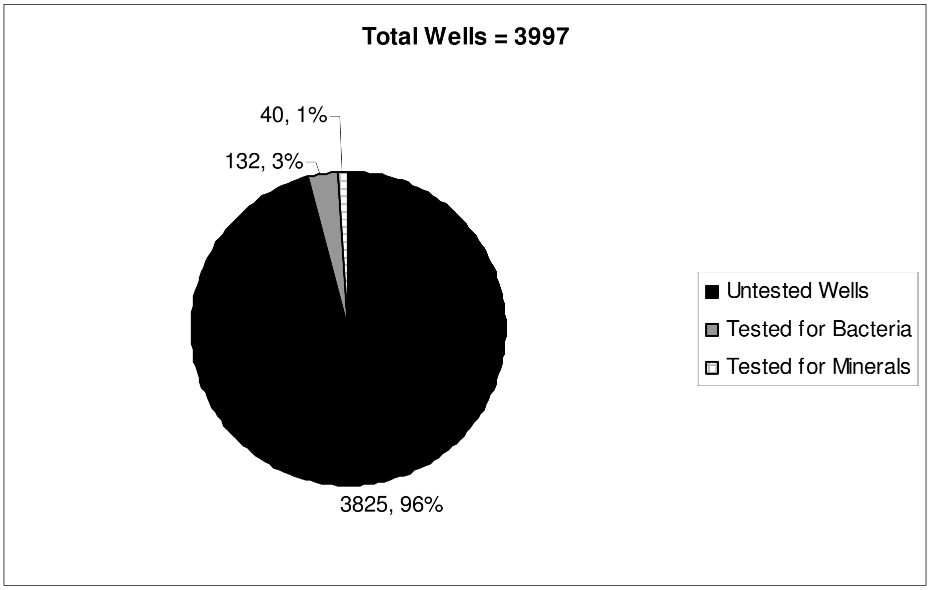


Figure 2. Graphical representation of wells tested and untested in Washington County.

All well tests were conducted between 2002 and 2008. The following table shows the breakdown of wells tested yearly.

The Number of Wells Tested Each Year	
Year	**# of Wells**
2002	5
2003	10
2004	3
2005	14
2006	4
2007	2
2008	2

Table 5. The number of wells tested yearly.

The soil type around the well was determined for the wells tested for minerals. The locations of the wells tested for bacteria content was unknown. The following table shows the soil types represented in the data set and number of wells in each.

The Number of Wells per Soil Type		
Soil Type	**Abreviation**	**# of Wells**
Ardilla-Persanti-Odilla	APO	1
Bibb-Kinston	BK	2
Cowarts-Nankin-Dothan	CND	1
Dothan-Tifton-Faceville	DTF	13
Lakeland-Lucy-Orangeburg	LLO	3
Orangeburg	O	1
Orangeburg-Faceville-Greenville	OFG	12
Unknown		7
Total		40

Table 6. The number of wells in the data set attributed to soil types.

pH

Wells in the county had an average pH of 6.76, a slightly acidic level. When the linear model was fit to the data, APO soil was found to be a significant predictor (p<0) of pH level. The output for the linear model follows.

```
Call:
lm(formula = log(minerals$pH) ~ minerals$soil)

Residuals:
      Min        1Q    Median        3Q       Max 
-0.203207 -0.088762  0.001105  0.062470  0.202258 

Coefficients:
                      Estimate Std. Error t value Pr(>|t|)    
(Intercept)           1.871802   0.109940  17.026   <2e-16 ***
minerals$soilBK       0.001064   0.134648   0.008    0.994    
minerals$soilCND      0.169418   0.155478   1.090    0.284    
minerals$soilDTF      0.028085   0.114090   0.246    0.807    
minerals$soilLLO     -0.066222   0.126947  -0.522    0.606    
minerals$soilO        0.169418   0.155478   1.090    0.284    
minerals$soilOFG      0.057510   0.114429   0.503    0.619    
minerals$soilunknown  0.017804   0.117530   0.151    0.881    
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 

Residual standard error: 0.1099 on 32 degrees of freedom
Multiple R-Squared: 0.1697,     Adjusted R-squared: -0.01199 
F-statistic: 0.934 on 7 and 32 DF,  p-value: 0.4943
```

However, when a Tukey honest significant differences analyses was run on the data, no significant differences were found between soil types. The plot of the 95% confidence intervals for this analysis follows (Figure 3). All of the intervals overlap indicating that the pH does not differ significantly among soil types.

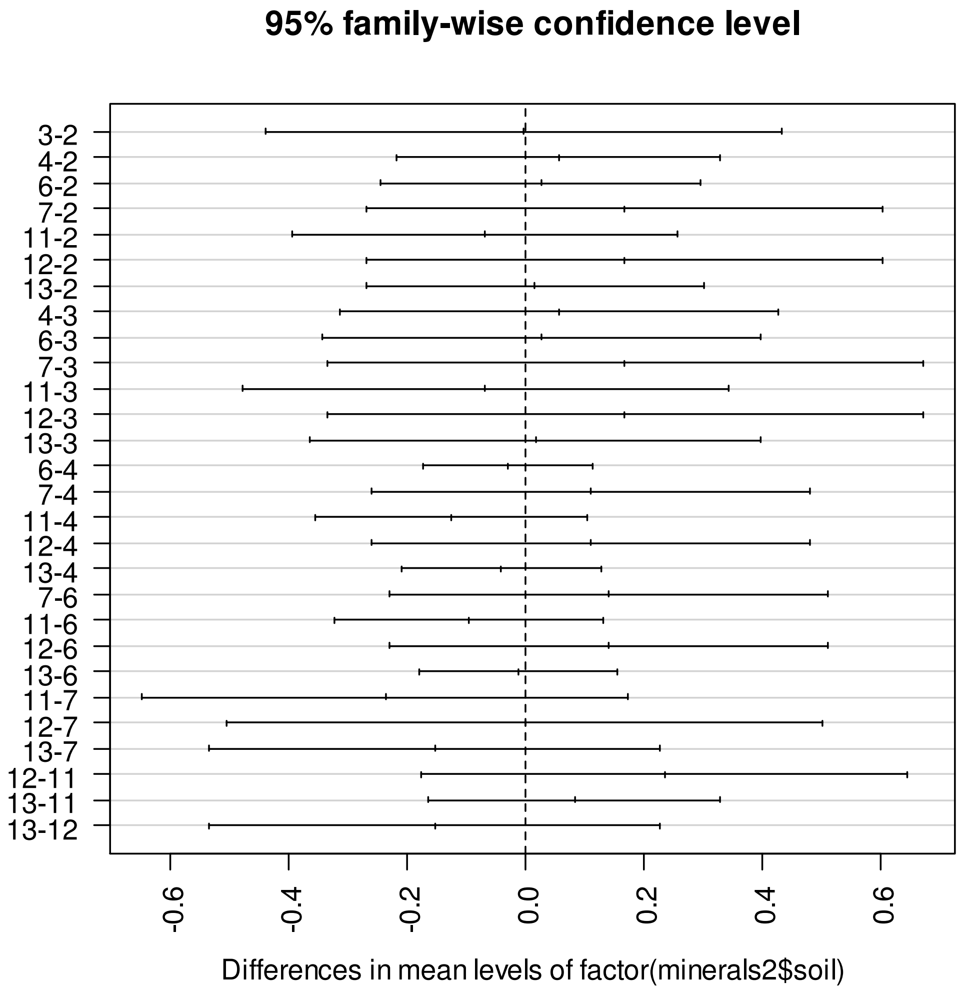


Figure 3. 2=BK; 3=APO; 4=OFG; 6=DTF; 7=CND; 11=LLO; 12=O; 13=unknown

When the linear model comparing pH to sample year was fit to the data, the years 2002 ($p<0$) and 2007 ($p<0.1$) were found to be a significant predictor of pH levels. However, as with soil type, no significant differences in pH levels were found when a Tukey honest significant differences analyses was conducted. The results of the linear model and the graph of the Tukey confidence intervals (Figure 4) follow.

```
Call:
lm(formula = log(minerals$pH) ~ factor(minerals$year))

Residuals:
      Min        1Q    Median        3Q       Max 
-0.211665 -0.073313  0.008223  0.074984  0.177289 

Coefficients:
                            Estimate Std. Error t value Pr(>|t|)    
(Intercept)                  1.93143    0.04772  40.476   <2e-16 ***
factor(minerals$year)2003 -0.04179    0.05844  -0.715   0.4796    
factor(minerals$year)2004  0.02013    0.07792   0.258   0.7978    
factor(minerals$year)2005 -0.05206    0.05559  -0.937   0.3558    
factor(minerals$year)2006 -0.05460    0.07158  -0.763   0.4510    
factor(minerals$year)2007  0.15422    0.08927   1.728   0.0934 .  
factor(minerals$year)2008 -0.03335    0.08927  -0.374   0.7111    
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 

Residual standard error: 0.1067 on 33 degrees of freedom
Multiple R-Squared: 0.1934,     Adjusted R-squared: 0.04676 
F-statistic: 1.319 on 6 and 33 DF,  p-value: 0.2765
```

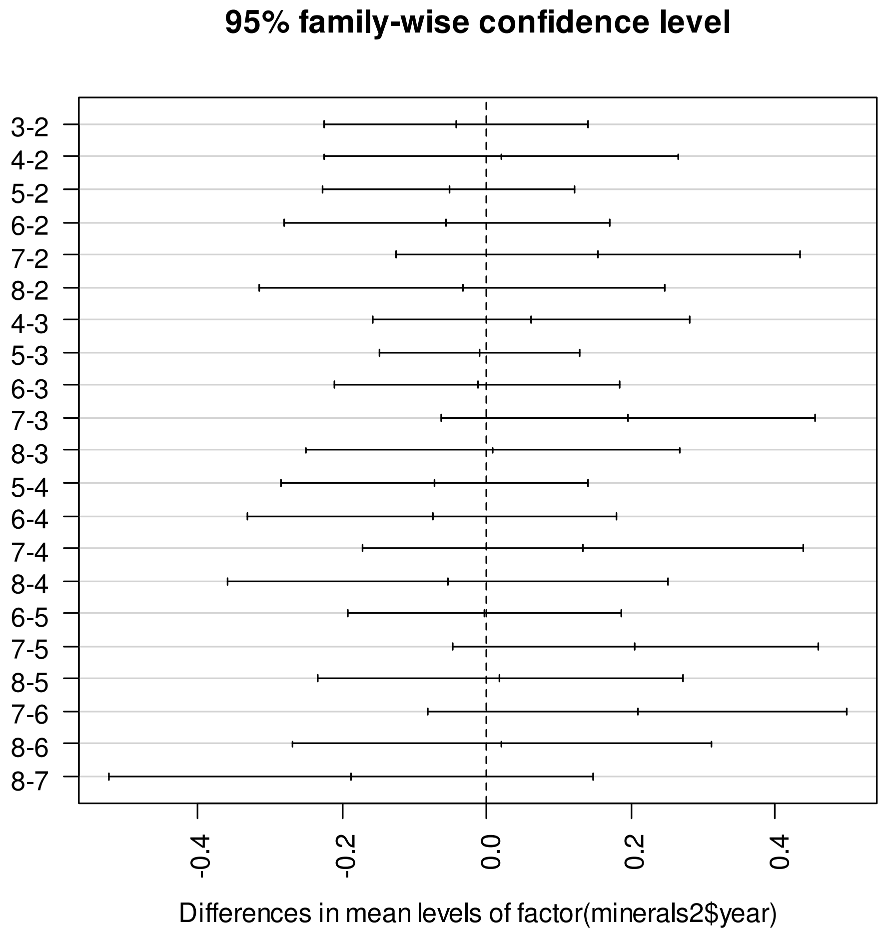


Figure 4. Years are represented by the last digit in the year.

Hardness

Wells in Washington County had an average hardness of 79.275 ppm. This value falls in the range which is considered medium hardness (Massachusetts Board of Health). All soils except for APO were found to be significant (p<.01) predictors of water hardness in the linear model. However, the Tukey honest significant differences analyses revealed that hardness did not differ by soil type. The linear model output and graph of the confidence intervals (Figure 5) follow.

```
Call:
lm(formula = log(minerals$hard) ~ minerals$soil)

Residuals:
       Min         1Q     Median         3Q        Max 
-2.036e+00 -7.369e-01  1.004e-16  9.656e-01  1.654e+00 

Coefficients:
                      Estimate Std. Error  t value Pr(>|t|)   
(Intercept)          7.964e-16  1.220e+00 6.53e-16  1.00000   
minerals$soilBK      3.602e+00  1.494e+00    2.411  0.02184 * 
minerals$soilCND     4.828e+00  1.725e+00    2.799  0.00862 **
minerals$soilDTF     3.558e+00  1.266e+00    2.811  0.00837 **
minerals$soilLLO     3.126e+00  1.409e+00    2.219  0.03369 * 
minerals$soilO       4.997e+00  1.725e+00    2.897  0.00675 **
minerals$soilOFG     4.233e+00  1.270e+00    3.334  0.00217 **
minerals$soilunknown 3.851e+00  1.304e+00    2.953  0.00585 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 

Residual standard error: 1.22 on 32 degrees of freedom
Multiple R-Squared: 0.3095,     Adjusted R-squared: 0.1584 
F-statistic: 2.049 on 7 and 32 DF,  p-value: 0.07903 
```

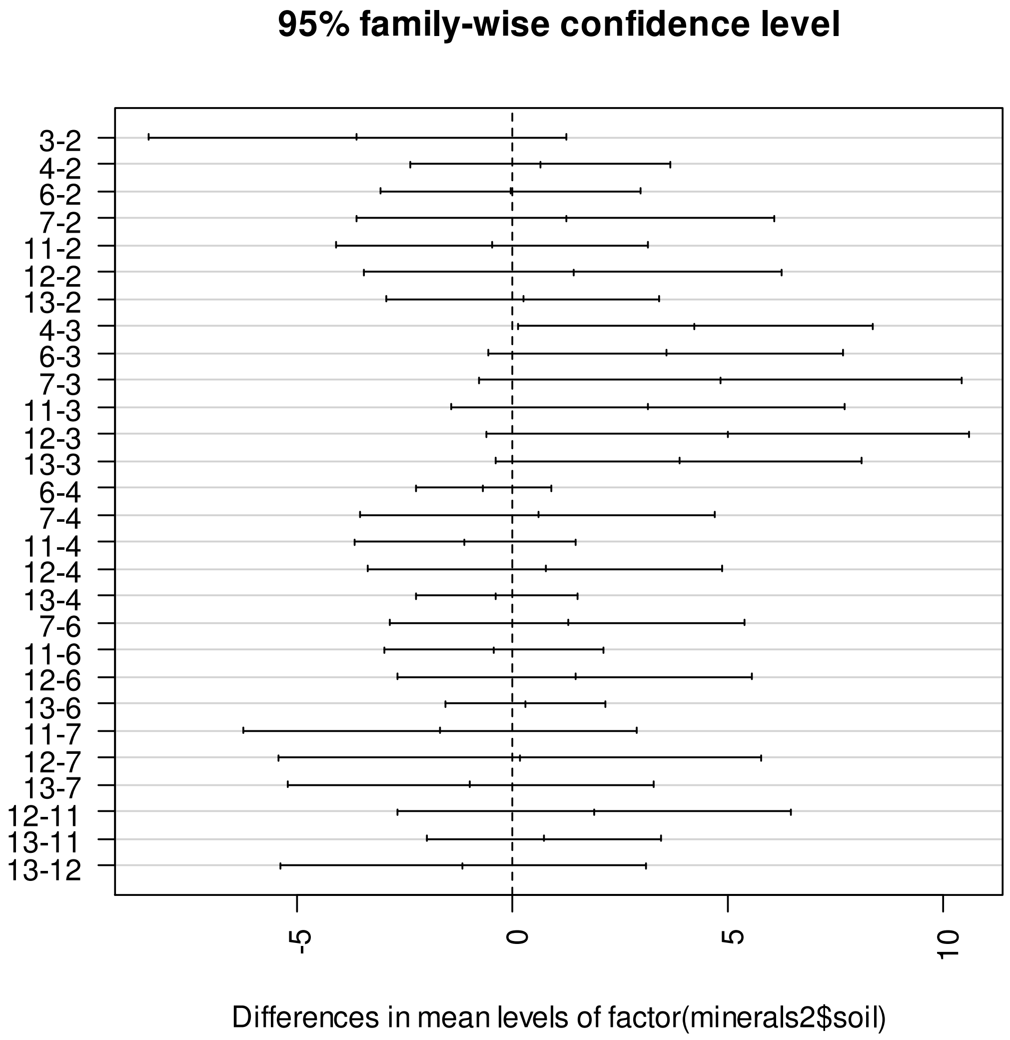


Figure 5. 2=BK; 3=APO; 4=OFG; 6=DTF; 7=CND; 11=LLO; 12=O; 13=unknown

The linear model comparing hardness to sample year indicated that the year 2002 was a significant predictor ($p<0$) of water hardness; however, the Tukey honest significant differences again revealed that hardness did not differ from year to year. The output of the linear model and the graph of the confidence intervals (Figure 6) follow.

```
Call:
lm(formula = log(minerals$hardness) ~ factor(minerals$year))

Residuals:
    Min      1Q  Median      3Q     Max 
-3.8162 -0.9367  0.2492  1.1523  1.7939 

Coefficients:
                            Estimate Std. Error t value Pr(>|t|)    
(Intercept)                   3.8162     0.6232   6.124  6.7e-07 ***
factor(minerals$year)2003   0.1569     0.7632   0.206    0.838    
factor(minerals$year)2004   0.3909     1.0176   0.384    0.703    
factor(minerals$year)2005  -0.3703     0.7260  -0.510    0.613    
factor(minerals$year)2006  -0.3422     0.9348  -0.366    0.717    
factor(minerals$year)2007   0.9641     1.1658   0.827    0.414    
factor(minerals$year)2008  -0.1721     1.1658  -0.148    0.884    
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 

Residual standard error: 1.393 on 33 degrees of freedom
Multiple R-Squared: 0.07086,    Adjusted R-squared: -0.09807 
F-statistic: 0.4195 on 6 and 33 DF,  p-value: 0.8607 
```

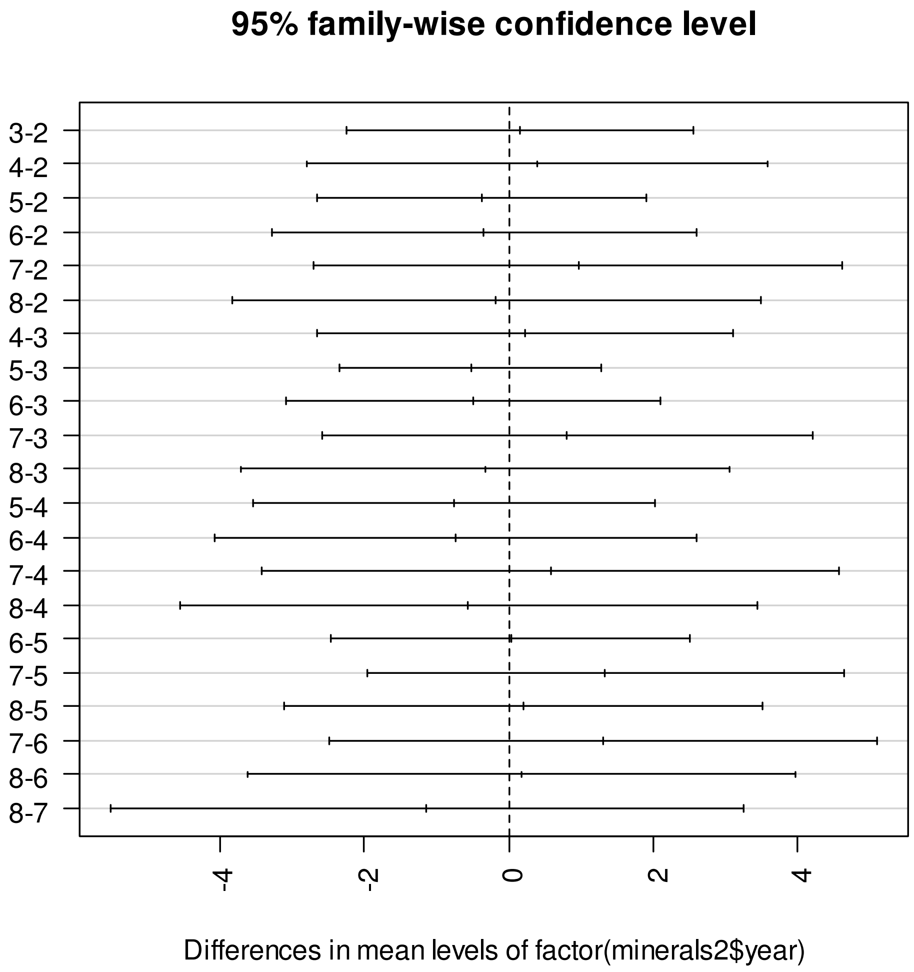


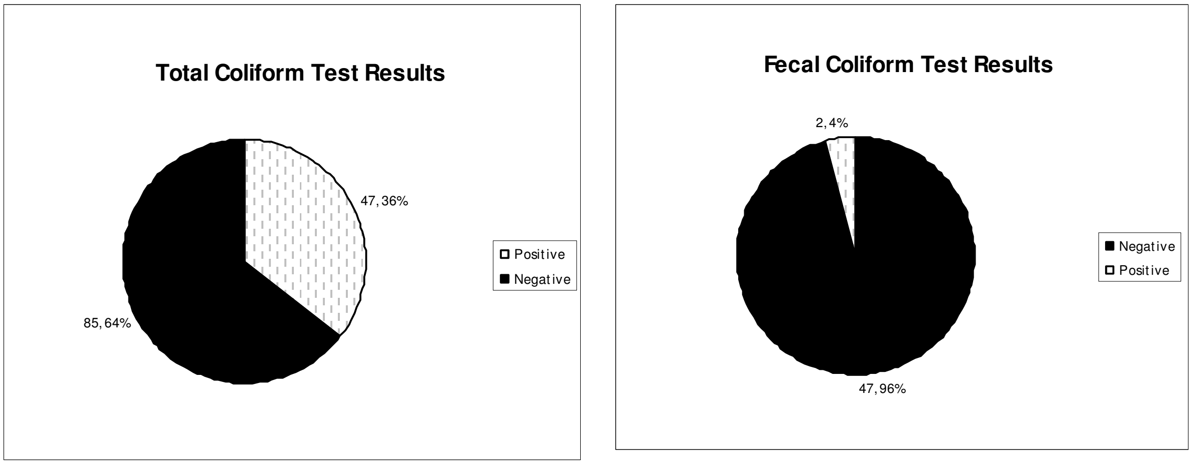
Figure 6. Years are represented by the last digit in the year.

Bacteria

The Washington County Health Department tests well water for total and fecal coliform bacteria. Of the 132 tests performed, only 47 were positive for total coliform bacteria. Of these 47 tests, only 2 were positive for fecal coliform bacterial. These results are shown in the following table.

Results of the Tests for Coliform Bacteria		
Test	**Total Coliform**	**Fecal Coliform**
Positive	47	2
Negative	85	130
Total	132	132

Table 7. Results of tests performed by the Washington County Health Department.



Figures 7 & 8. In Washington County, 35.6% of wells tested had coliform bacteria present. Only 4.3% of these also had fecal bacteria present. 64.4% of the wells tested in the county proved negative for coliform bacteria. 98.4% of wells tested did not have fecal bacteria present.

Aluminum

Kaolin is aluminum silicate. Because many kaolin mines are located within Washington County, aluminum and silica were chosen from the mineral test data for analysis. The following table shows the results of these data.

Aluminum and Silica Data Results							
	Total	Det lim (ppm)	# below det lim	Avg (ppm)	Range (ppm)	EPA Standard (ppm)	Probability Exceeding Standard (%)
Al	40	0.025	28	0.044	Neg – 1.71	0.2	25.5
SiO2	40	0.01	0	28.35	9.24 – 51.96	n/a	n/a

Table 8. Avg = average; det lim = detection limit; neg = negiglible (the data that were below detection limits).

Because it is not considered to be a threat to human health but can be a nuisance by coloring the water, the EPA established a secondary drinking water standard of 0.2 ppm for aluminum. A large number of data were below detection limit for this mineral; therefore, an expected maximization algorithm was used for statistical analysis. A well in Washington County was determined to have a 25.5% probability of exceeding the EPA standard while only two of the 40, or 5%, wells exceeded the standard. It is important to note, however, that 70% of the data points were below the detection limit of 0.025 ppm. Therefore, these results might be overpredicting aluminum risk.

When a linear model comparing Al level to soil type was fit to the data, BK, CND, DTF, LLO, and OFG soils were found to be significant ($p<.001$) predictors of aluminum level. Only APO and O soil types were not found to be significant predictors of aluminum level. Additionally, the unknown soils were found to be significant ($p<.001$).

When a linear model comparing Al to sample year was fit to the data, all years were found to be significant predictors of Al level. The results of the EM linear model algorithm follow.

Results of the linear model for soil type.

EM.lm (tempAl2, minerals$soil, log(0.025), .001)

```
           Estimate Std. Error     t value     Pr(>|t|)
xAPO      0.5364934  0.9531198   0.5628814 5.774385e-01
xBK      -4.3058943  0.6739575  -6.3889703 3.536969e-07
xCND     -4.3058943  0.9531198  -4.5176842 8.023980e-05
xDTF     -3.6855185  0.2643479 -13.9419261 3.819973e-15
xLLO     -4.3058943  0.5502840  -7.8248586 6.316061e-09
xO       -1.6094379  0.9531198  -1.6885998 1.010196e-01
xOFG     -3.5091502  0.2751420 -12.7539611 4.328491e-14
xunknown -3.8204896  0.3602454 -10.6052410 5.280550e-12
```

Results of the linear model for year of sample.

EM.lm (tempAl2, factor(minerals$year), log(0.025), .001)

```
       Estimate Std. Error    t value     Pr(>|t|)
x2002 -2.064821  0.3890349  -5.307547 7.444221e-06
x2003 -2.762954  0.2750892 -10.043847 1.450800e-11
x2004 -4.343505  0.5022419  -8.648232 5.385740e-10
x2005 -4.343505  0.2324928 -18.682316 4.061970e-19
x2006 -4.343505  0.4349543  -9.986118 1.676263e-11
x2007 -4.343505  0.6151182  -7.061252 4.410518e-08
x2008 -4.343505  0.6151182  -7.061252 4.410518e-08
```

A Tukey honest differences analyses was run on the aluminum data. It is important to note, however, that the analysis was run on the original data, using the detection limit for all samples found to be negligible. The EM algorithm results were not used for this analysis. Al was not found to differ significantly among years or soil types. The graphs of the Tukey confidence intervals follow (Figures 9 & 10).

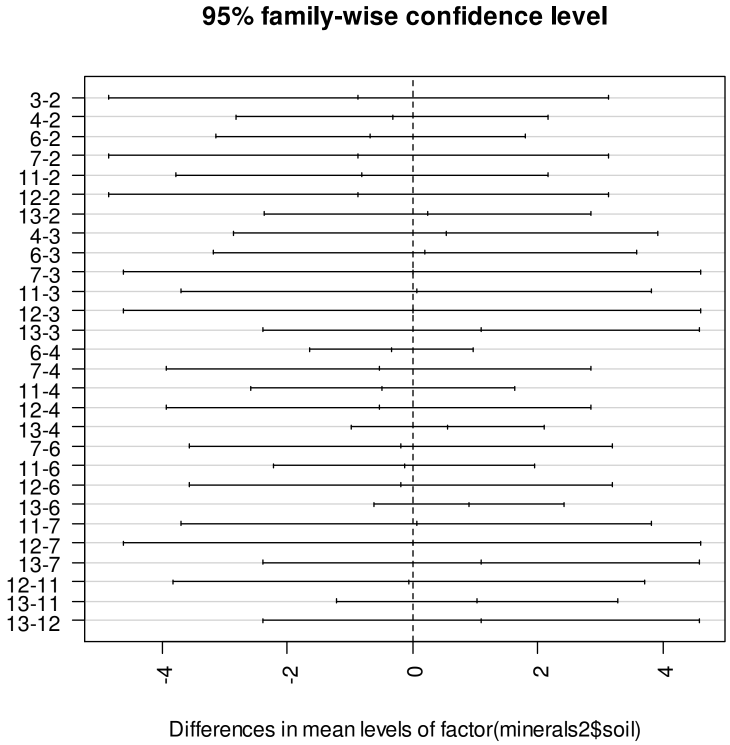


Figure 9. 2=BK; 3=APO; 4=OFG; 6=DTF; 7=CND; 11=LLO; 12=O; 13=unknown

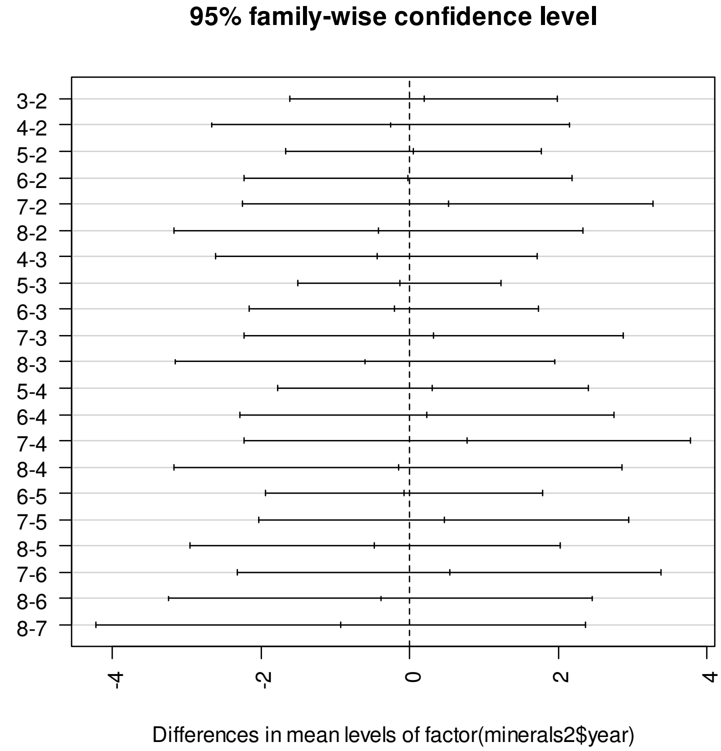


Figure 10. Years are represented by the last digit in the year.

Silica

100% of the silica data were above detection limit; therefore, the expected maximization algorithm was not used to analyze them. The average silica level for the county was 28.35 (+/- 1.56) ppm. The results ranged from 9.24 ppm to 51.96 ppm. No standard has been set by the EPA for this mineral because silica has a low toxicity when ingested and is not considered to be a threat to human health. However, it can cause scaling in pipes (Massachusetts Board of Health). Therefore, the level of 51.96 ppm that was found represents a nuisance threat. Additionally, the silica level of natural water tends to fall in the 1 to 30 ppm range. Therefore, the wells in the county, on average, fall at the higher end of normal levels.

A linear model comparing silica level to soil type was fit to the data and APO was found to be a significant predictor ($p<0$) of silica level. However, a Tukey honest significant differences analysis was run; and no significant differences were found among the soil types. The output of the linear model and the graph of the Tukey confidence intervals (Figure 11) follow.

```
Call:
lm(formula = log(minerals$SiO2) ~ minerals$soil)

Residuals:
     Min       1Q   Median       3Q      Max
-1.09894 -0.21165  0.06475  0.30064  0.69360

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)          3.32468    0.46576   7.138 4.22e-08 ***
minerals$soilBK     -0.35816    0.57044  -0.628    0.535
minerals$soilCND     0.19933    0.65869   0.303    0.764
minerals$soilDTF     0.12196    0.48335   0.252    0.802
minerals$soilLLO    -0.12197    0.53782  -0.227    0.822
minerals$soilO      -0.45905    0.65869  -0.697    0.491
minerals$soilOFG    -0.00219    0.48478  -0.005    0.996
minerals$soilunknown  0.08391    0.49792   0.169    0.867
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.4658 on 32 degrees of freedom
Multiple R-Squared: 0.1008,     Adjusted R-squared: -0.0959
F-statistic: 0.5124 on 7 and 32 DF,  p-value: 0.8183
```

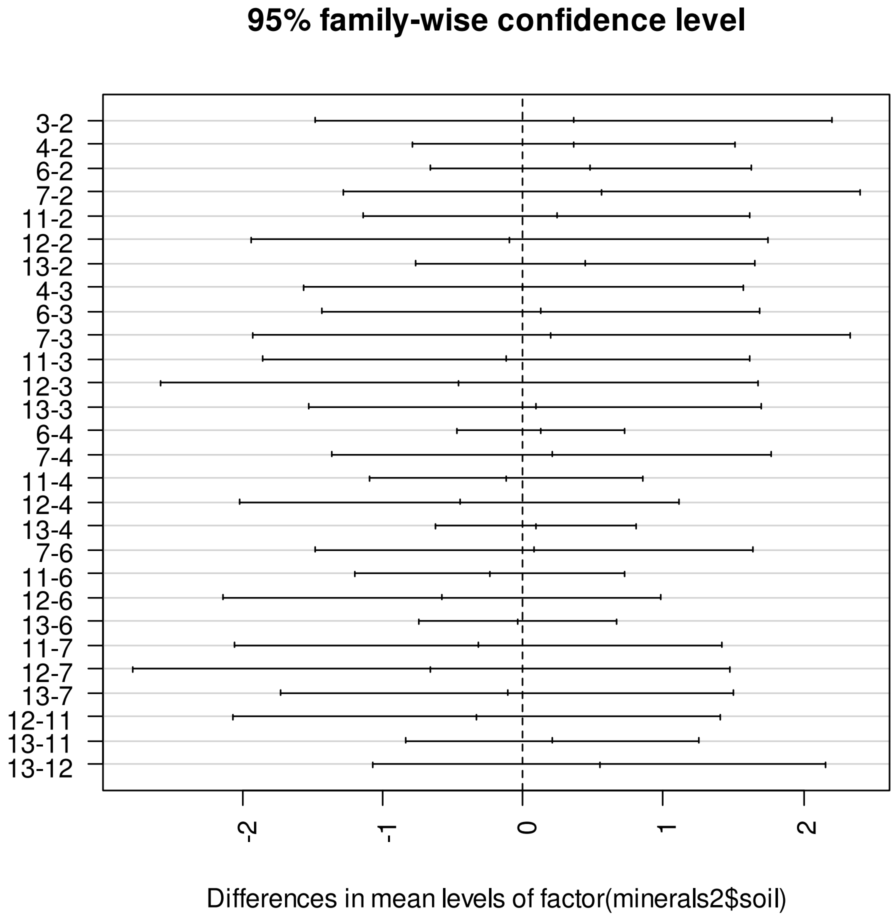


Figure 11. 2=BK; 3=APO; 4=OFG; 6=DTF; 7=CND; 11=LLO; 12=O; 13=unknown

The year 2002 was found to be a significant predictor ($p<0$) when the linear model comparing silica to sample year was fit to the data; however, the Tukey honest significant differences analysis again revealed that silica level did not differ significantly from year to year. The output of the linear model and the graph of the Tukey confidence intervals (Figure 12) follow.

```
Call:

lm(formula = log(minerals$SiO2) ~ factor(minerals$year))

Residuals:
     Min       1Q   Median       3Q      Max
-0.94406 -0.21925  0.04502  0.30725  0.74722

Coefficients:
                            Estimate Std. Error t value Pr(>|t|)
(Intercept)                  3.36206    0.20431  16.456   <2e-16 ***
factor(minerals$year)2003  0.13167    0.25022   0.526    0.602
factor(minerals$year)2004  0.04831    0.33363   0.145    0.886
factor(minerals$year)2005 -0.19446    0.23801  -0.817    0.420
factor(minerals$year)2006  0.06244    0.30646   0.204    0.840
factor(minerals$year)2007 -0.07315    0.38222  -0.191    0.849
factor(minerals$year)2008  0.23319    0.38222   0.610    0.546
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.4568 on 33 degrees of freedom
Multiple R-Squared: 0.1079,     Adjusted R-squared: -0.05431
F-statistic: 0.6651 on 6 and 33 DF,  p-value: 0.6781
```

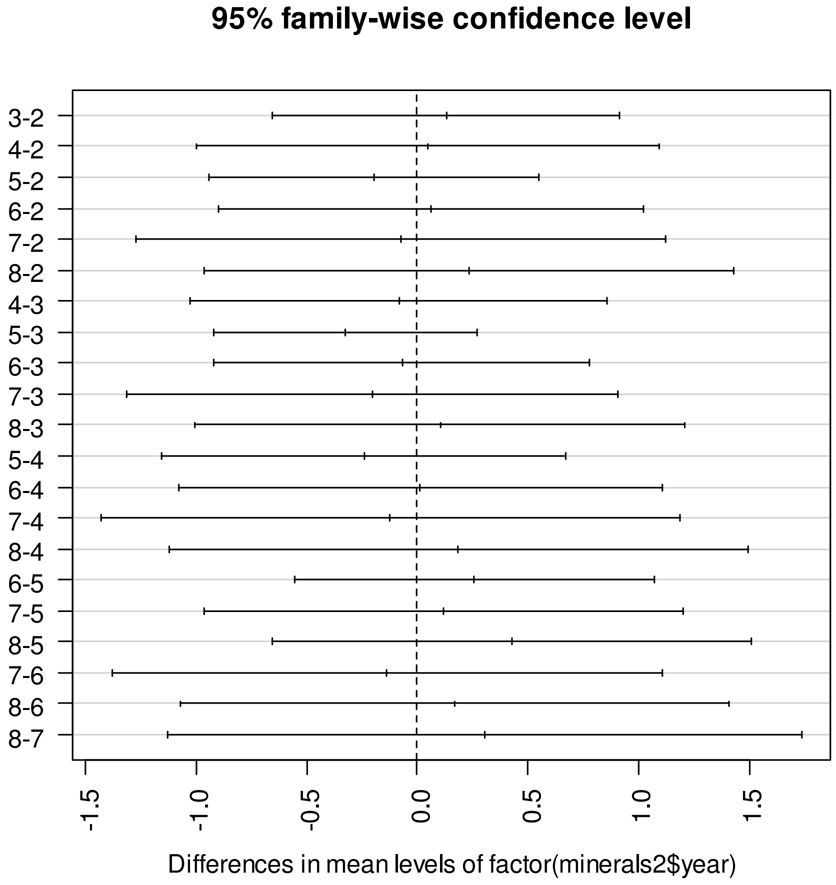


Figure 12. Years are represented by the last digit in the year.

Manganese

Manganese was chosen from the available mineral data to provide another example of a regulated mineral. The EPA has established a secondary drinking water standard of 0.05 ppm for manganese. It can produce bad taste and black sediment in the water; it can also stain laundry and plumbing (ATSDR). It is, therefore, not considered a threat to human health by the EPA. However, it has been shown to cause adverse health effects in human such as impairment of motor skills and cognitive dysfunction at high levels. The following table presents the data.

Manganese Data Results							
	Total	**Det lim (ppm)**	**# below det lim**	**Avg (ppm)**	**Range (ppm)**	**EPA Standard (ppm)**	**Probability Exceeding Standard (%)**
Mn	40	0.005	1	0.007	Neg – 0.31	0.05	17.1

Table 9. Avg = average; det lim = detection limit; neg = negiglible (the data that were below detection limits).

Like aluminum, manganese data were below the detection limit of 0.005 ppm; and the expected maximization algorithm was applied. This data set was more complete, however, because only one, or 2.5%, of these data was below detection. Wells in Washington County had an average manganese level of 0.007 ppm. The predicted probability of exceeding the standard, 17.1%, was much closer to the percentage of wells that actually exceeded the standard. Five, or 12.5%, of the wells were above the standard. All soil types and years were found to be significant predictors (p<.001) of manganese level. The output of the EM linear models follow.

Results of the linear model for soil type.

EM.lm (tempMn2, minerals$soil, log(0.015))

```
          Estimate Std. Error    t value     Pr(>|t|)
xAPO     -2.813411  1.0196540  -2.759182 9.503961e-03
xBK      -4.887667  0.7210043  -6.778971 1.161907e-07
xCND     -4.887667  1.0196540  -4.793456 3.618723e-05
xDTF     -3.900091  0.2828011 -13.790931 5.157396e-15
xLLO     -3.473452  0.5886975  -5.900233 1.449131e-06
xO       -3.218876  1.0196540  -3.156831 3.466206e-03
xOFG     -4.363558  0.2943488 -14.824447 6.920613e-16
xunknown -4.465711  0.3853930 -11.587421 5.480778e-13
```

Results of the linear model for year of sample.

EM.lm (tempMn2, factor(minerals$sample), log(0.015))

```
       Estimate Std. Error    t value     Pr(>|t|)
x2002 -3.083396  0.4320909  -7.135989 3.561722e-08
x2003 -4.136833  0.3055344 -13.539662 5.005328e-15
x2004 -3.776868  0.5578270  -6.770680 1.017590e-07
x2005 -4.176204  0.2582237 -16.172812 3.004409e-17
x2006 -4.877318  0.4830924 -10.096036 1.273665e-11
x2007 -4.877318  0.6831958  -7.138976 3.531464e-08
x2008 -4.877318  0.6831958  -7.138976 3.531464e-08
```

A Tukey honest differences analyses was run on the manganese data. It is important to note, however, that the analysis was run on the original data, using the detection limit for all samples found to be negligible. The results of the EM algorithm were not used for this analysis. Mn was not found to differ significantly among years or soil types. The graphs of the Tukey confidence intervals follow (Figures 13 & 14).

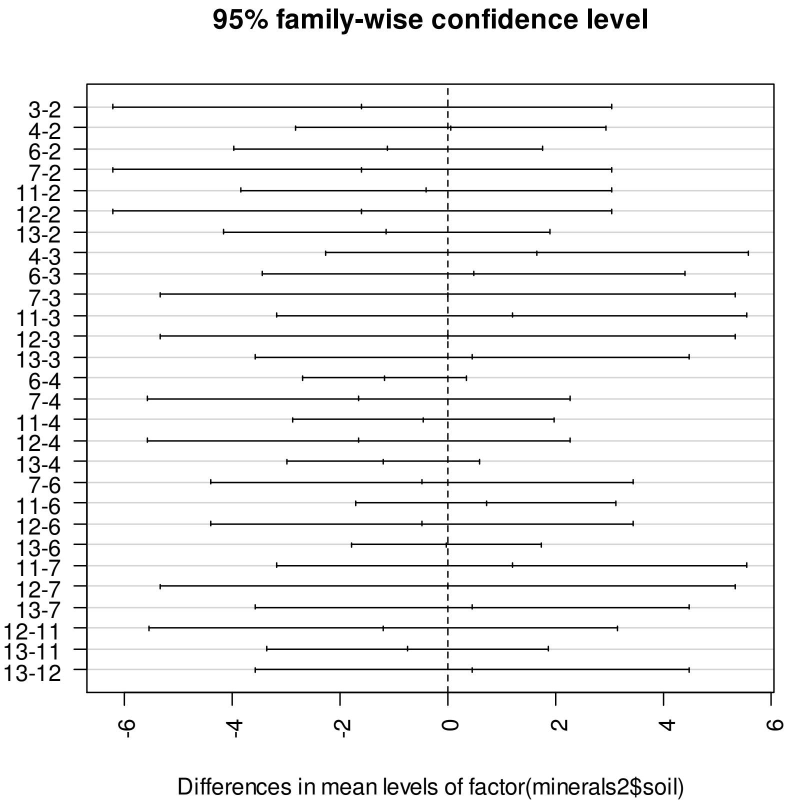


Figure 13. 2=BK; 3=APO; 4=OFG; 6=DTF; 7=CND; 11=LLO; 12=O; 13=unknown

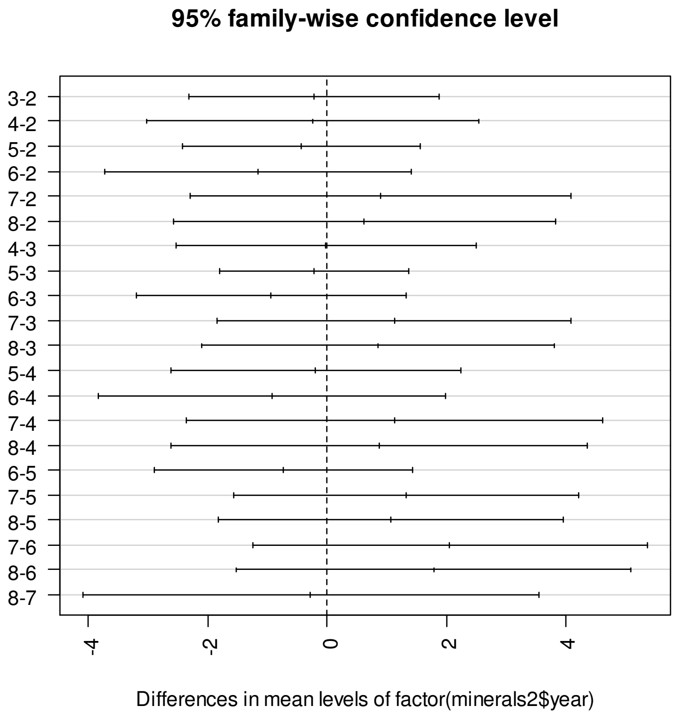


Figure 14. Years are represented by the last digit in the year.

Conclusions

The goal of this project was to perform a basic analysis of available well test data for Washington County, Georgia. Private well owners are not protected under the Safe Drinking Water Act and are, therefore, responsible for the safety of their drinking water. It is well established that contaminants such as nitrates, volatile organic compounds, metals, and bacteria are potential threats to well water quality and possibly to the health of well water consumers. Unique problems, however, face individual counties due to geology, mining practices, farming practices, and other local phenomena. In Washington County, Georgia, the runoff from the kaolin industry has the potential to increase levels of aluminum and silica in well water. Agricultural runoff is potential source of nitrate and bacterial contamination.

132 wells were tested for the presence of coliform bacteria. Only 35.6% of them had coliform bacteria; only 4.3% of these also had fecal bacteria present. These data seems to suggest a low occurrence of bacterial contamination in Washington County. . 64.4% of the wells tested in the county did not contain coliform bacteria. 98.4% of wells tested did not have fecal bacteria present. However, it is important to note that the wells tested represent only 3.3% of the total number of wells in the county.

Although the kaolin industry in the county has implemented environmental controls, kaolin dust can still be found along roadways near mines. After rainfall, the runoff could potentially enter wells, especially those that are older and poorly constructed. It was expected that aluminum and silica levels in the county would be high because kaolin is aluminum silicate. The average aluminum level for Washington County was 0.044 ppm. A well in Washington County has only a calculated 25.5%

probability of exceeding the aluminum standard of 0.2 ppm set by the EPA; additionally, only 5% of the wells actually exceeded the standard. The average silica level for the county was 28.35 ppm. This value falls into the higher range of silica level, 1 to 30 ppm, considered normal for natural water (Massachusetts Board of Health). Based on these data, Washington County does not seem to have unusually high levels of silica or aluminum. However, one well had a silica level of 51.96 ppm, suggesting that some well owners might face a nuisance threat from silica.

The average manganese level Washington County was 0.007 ppm. Only one sample was below the detection limit for manganese. Wells in this county were calculated to have only a 17.1% chance of exceeding the EPA standard of 0.05 ppm while only 12.5% of the samples actually exceeded the standard. On average, wells in Washington County were found to have slightly acidic pH (6.76) and medium water hardness (79.725 ppm). These data suggest that Mn, pH, and water hardness are not significant threats to the wells in the county.

It was hypothesized that contaminant levels would vary by soil type. Therefore, linear models were fit to the data; and Tukey honest significant differences analysis was applied to the data. Five (BK, CND, DTF, LLO, and OFG) of the seven known soil types were predictive of Al level. Additionally, the soil type around some of the wells was unknown. Unknown soil type was also a significant predictor of Al level. When a Tukey honest differences analysis was run, however, no significant differences were discovered among the soil types. For silica, APO soil was found to be a significant predictor; however, silica level did not differ significantly among the soil types. For Mn, all soil types were found to be a significant predictor of manganese level in the county; however, Mn levels did not differ significantly by soil type. For pH, APO soil type was found to be significant predictors. For hardness, all soils except APO were found to be significant predictors. As with the minerals, however, hardness and pH did not differ significantly among the soil types.

It is not recommended at this time for officials in this county to focus monitoring and well quality education efforts on a particular soil type. No consistency was found for significant predictors in the linear models among the variables assessed, but analysis did consistently reveal no significant differences among the soil types. These results are somewhat surprising because soil type is generally considered to affect water quality. Some soils act as better natural filters than others (Borchardt, Wojcik). It is important to note the small sample size. This resulted in unequal numbers of wells in the different soil types, with some of them only containing one well. It is also important to note that due to the resolution in the locations given for each well soil type might have been incorrectly identified. Another important limitation with these results is that the results of the EM algorithm could not be used for the Tukey analysis of Al and Mn; the detection limits were substitutes for the missing data points.

It was also hypothesized that contaminant levels would vary by year. All years were predictive of Al level; however, no significant differences were discovered among the years of sample. For silica, the year 2002 was found to be a significant predictor; however, silica level did not differ significantly among years. For Mn, all years were found to be significant predictors of manganese level in the county; however, Mn levels did not differ significantly by year. For pH, the year 2002 was found to be a significant predictor. For hardness, the year 2002 was found to be a significant predictor. As with the minerals, however, hardness and pH did not differ significantly among years. These data suggest that from 2002 until 2008, water quality was consistent in Washington County.

Perhaps spatial relationship is an issue of more concern than soil type or year. As mentioned previously, the kaolin industry in the county represents a potential source of well contamination; however, aluminum and silica levels were not determined to be significantly high with these data. Also, they did not differ by soil type. Wells that are closer to kaolin mines might be at greater risk from contamination by kaolin containing runoff. Future research in Washington County should address this issue.

Despite the somewhat encouraging results of the analyses, well water quality is an important issue in Washington County. An estimated 45% of the population received their drinking water from private wells in 2000. That number is increasing. By 2008, the number of wells had risen from 3,849 to 3,997. However, only 4.3% of these wells were tested. Washington County officials should, therefore, initially focus their efforts on mining more data. They could acquire a better database by requiring homeowners to have their wells tested more often.

Although it is recommended, testing of newly dug wells is not required in the county. Permits must be required for new wells, and the homeowners must be required to submit test data to the Health Department and Extension Office. Additionally, Washington County could follow the lead of other communities like Randolph Township, New Jersey, where homeowners are required to test their well water before selling their home (Tabbott). By requiring testing at well construction and when a home is sold, Washington County could quickly build a larger database of mineral and coliform testing.

Payment for these tests must, however, be addressed. Currently, homeowners request and pay for their own testing. The fee for the coliform testing is $40. The Health Department grants fee waivers only if members of the household are experiencing gastrointestinal illness. Cost associated with a mineral test is $10. The fact that homeowners must pay for their tests suggests that the existing data are biased toward more affluent members of the Washington County population. The available data are possibly also biased towards homeowners with a greater awareness of water quality concerns. It also suggests that homeowners might not accept a law requiring them to pay for extra testing. To address this problem, Washington County could apply for state grants and establish a fund to help homeowners pay for testing or allow homeowners to apply for a waiver of testing if they do not meet minimum income requirements. Requiring testing before a homeowner sells their house could pose a legal issue, also. If the well water is out of compliance, the homeowner might not be able to sell the house or might be found liable for its remediation. Ensuring confidentiality to the homeowner could help alleviate these problems.

It is also recommended that Washington County focus efforts on testing wells for other contaminants. Even though volatile organic compounds and nitrates have been identified as contaminants in other rural areas in the United States, no data were available on these contaminants in Washington County. As mentioned earlier, family farms are still in operation in Washington County. The presence of agriculture represents a source of nitrates; these should be tested for. The Extension Office should make a policy of telling every homeowner requesting mineral testing what other contaminants can be tested. Simple educational efforts such as this would increase awareness among homeowers. Additionally, studies have found that risk communication is very important because well owners often do not know contaminant levels in their wells (Shaw).

The Extension Office and Health Department would benefit from a combined database. It was not possible to analyze correlations between bacteria levels and soil or between bacteria levels and minerals because the bacteria and mineral tests could not be matched. A master database with the location of the well, soil type in that location, bacteria levels, and mineral levels would allow greater statistical analysis and increase statistical power. A database of this kind could lead to contaminant mapping and plume determination.

For this project, the total number of wells in the county had to be estimated from census data and well permits. Many assumptions were made for this count. These assumptions include the following: these houses only have one private well each, an intent-to-drill form was completed for all new wells dug between 2001 and 2008, and these wells were dug for new houses and not to replace dry wells at existing houses. It was also not possible to determine the total number of old wells in the county. These wells, in particular, pose a physical hazard and entry point for contaminants into the groundwater. Washington County must begin to assess the true number of wells in the county. A simple start would be sending out surveys to homeowners to declare the wells on their property. Citizens of Washington County might resist these efforts if implemented by the county. Surveys have shown that many well owners prefer their well water to municipal water (NGWA). Additionally, the required cost and potential privacy violations will raise homeowners' concerns. However, with an estimated 45% of the population relying on well water, the county must examine efforts to build a better database of not only contaminants levels but also wells present.

This project filled an important knowledge gap in Washington County, Georgia, where the available data had not been previously analyzed. A simple analysis of well water quality in Washington County, Georgia, revealed that the contaminants tested might not pose a significant threat to homeowners. Total and fecal coliform bacteria, manganese, aluminum, and silica were examined. An assessment of the county revealed, however, that much improvement is needed to fill holes in the available data. As proven in other rural areas in the United States, well owners face contamination from many sources. However, they are not protected under the Safe Drinking Water Act. It is vitally important that the Washington County Health Department and UGA Extension Office continue their current efforts and begin coordinating their efforts and expanding their programs. The results of the analyses were encouraging. Therefore, every effort should be made to continue to improve water quality for well owners in Washington County, Georgia.

References

Aelion, C.M. and Conte, B.C. 2004. Susceptibility of residential wells to VOC and nitrate contamination. *Environ. Sci. Technol.* 38: 1648-1653.

Agency for Toxic Substances and Disease Registry (ATSDR). 2005. Health Consultation: Private well water quality, Williamson WV sites. April 6.

Ayotte, Joseph D, D Baris, KP Cantor, J Colt, GR Robinson, Jr, JH Lubin, M Karagas, RN Hoover, JF Fraumeni, Jr, and DT Silverman. 2006. Bladder cancer mortality and private well use in New England: an ecological study. *J. Epidemiol. Community Health*. 60: 168-172.

Benson, Victoria S, JA VanLeeuwen, J Sanchez, IR Dohoo, and GH Somers. 2006. Spatial Analysis of Land Use Impact on Ground Water Nitrate Concentrations. *Journal of Environmental Quality*. 35 (2): 421-432.

Borchardt, Mark A, NL Hass, and RJ Hunt. 2004. Vulnerability of drinking-water wells in La Crosse, Wisconsin, to enteric-virus contamination from surface water contributions. *Applied and Environmental Microbiology*. 70 (10): 5937-5946.

Fishbein, L. 1979. Potential halogenated industrial carcinogenic and mutagenic chemicals. I. Halogenated unsaturated hydrocarbons. Sci Tot Environ. 11: 111-161.

Focazio, Michael J, D Tipton, SD Shapiro, and LH Geiger. 2006. The chemical quality of self-supplied domestic well water in the United States. *Ground Water Monitoring and Remediation*. 26 (3): 92-104.

George, Christine M, AH Smith, DA Kalman, and CM Steinmaus. 2006. Reverse osmosis filter use and high arsenic levels in private well water. *Archives of Environmental and Occupational Health*. 61 (4): 171-175.

Georgia Law Code. http://www.lexis-nexis.com/hottopics/gacode/default.asp

Landmeyer, James E. 1996. Aquifer response to record low barometric pressures in the southeastern United States. *Ground Water*. 34 (5): 917-924.

Law, Sidney. 2008. University of Georgia Extension Agent, Washinton County. Personal Interview. January.

Leeth, David C. 2007. Ground-water conditions in Georgia, 2005. *Proceedings of the 2007 Georgia Water Resources Conference*. University of Georgia, March 27-29.

Logue, James N, RM Stroman, D Reid, CW Hayes, and K Sivarajah. 1985. Investigation of potential health effects associated with well water chemical contamination in Londonberry Township, Pennsylvania, USA. *Archives of Environmental Health*. 40 (3): 155-160.

Lu, Jingrang, J Santo Domingo, and OC Shanks. 2007. "Identification of chicken-specific fecal microbial sequences using a metagenomic approach." *Water Research*. 41: 3561-3574.

Massachusetts Board of Health. Private Well Regulations. http://www.walpole-ma.gov/BOHDocs/PrivateWell.pdf

Mitchell, Thomas J, and AK Harding. 1996. Who is drinking nitrate in their well water? A study conducted in rural northeastern Oregon. *Environmental Health*. Oct: 14-19.

National Groundwater Association (NGWA). 2001. Ground water awareness week survey shows water wells owners confident of their drinking water. *Water Well Journal*. 55(17): 10.

Overacre, Lora. 2001. Domestic Well Water Testing Project 2000. Project Report 42. Atlanta. GA N200.G4 S1 P7 no. 42.

Poe, GL, HM van Es, TP Vandenberg, and RC Bishop. 1998. Do participants in well water testing programs update their exposure and health risk perceptions? *Journal of Soil and Water Conservation*. 53 (4): 320-325.

Robson, Mark, and D Schneider. 2001. Environmental health issues in rural communities. *Environmental Health*. June: 16-19.

Rowe, Barbara L, PL Toccalino, MJ Moran, JS Zogorski, and CV Price. 2007. Occurrence and potential human-health relevance of volatile organic compounds in drinking water from domestic wells in the United States. *Environmental Health Perspectives*. 115 (11): 1539-1546.

Santo Domingo, Jorge W, DG Bambic, TA Edge, and S Wuertz. 2007. "Quo vadis source tracking? Towards a strategic framework for environmental monitoring of fecal pollution." *Water Research*. 41: 3539-3552.

Schwarzenbach, R.P., Gschwend, P.M., and Imboden, D.M. 2003. Environmental Organic Chemistry, second edition. John Wiley & Sons, Inc. 592-598, 1200.

Shaw, W Douglass, M Walker, and M Benson. 2005. Treating and drinking well water in the presence of health risks from arsenic contamination: results from a US hot spot. *Risk Analysis*. 25 (6): 1531-1543.

Simpson, Hugh. 2004. Promoting the management and protection of private water wells. *Journal of Toxicology and Environmental Health, Part A*. 67: 1679-1704.

Simpson, Joyce M, JW Santo Domingo, and DJ Reasoner. 2002. "Microbial Source Tracking: State of the Science." *Environmental Science and Technology*. 36 (24): 5279-5288.

Smith, Jason. 2008. Department of Health Officer, Washinton County. Personal Interview. April.

Swistock, Bryan R, and WE Sharpe. 2005. The influence of well construction on bacterial contamination of private water wells in Pennsylvania. *Journal of Environmental Health*. 68 (2): 17-22.

Tabbot, Peter N, and MG Robson. 2006. The New Jersey residential well-testing program – a case study: Randolph Township. *Journal of Environmental Health*. 69 (2): 15–19.

Telsey, Albert I. 2002. Well water rising – in prominence, that is. *New Jersey Law Journal*. 169: 1324-1326.

Tuthill, Anna, DB Meikle, and MCR Alavanja. 1998. Coliform bacteria and nitrate contamination. *Journal of Environmental Health*. 60 (8): 16-20.

Van Every, Lynn R, and SD Dawson. 1995. Groundwater as a vehicle for disease transmission in southeastern Idaho: A case study. *Environmental Health*. December: 16-19.

United States Department of Agriculture (USDA). Soil Conservation Service in cooperation with the University of Georgia College of Agriculture Agricultural Experiment Stations. 1985. "Soil Survey of Washington and Wilkinson Counties, Georgia." October.

United States Environmental Protection Agency (USEPA). 2005. "Microbial Source Tracking Guide Document." National Risk Management Research Laboratory. June.

United States Environmental Protection Agency (USEPA). 2007a. Safe Drinking Water Information System (SDWIS): Violation Report for Tennille, GA. http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=GA3030006&state=GA&source=Purch_groundwater&population=1717&sys_num=0

United States Environmental Protection Agency (USEPA). 2007b. "Surf your watershed: Washington County." http://cfpub.epa.gov/surf/huc.cfm?huc_code=03060201. October 1.

United States Environmental Protection Agency (USEPA). 2007c. "Surf your watershed: Upper Ogeechee Watershed." http://cfpub.epa.gov/surf/county.cfm?fips_code=13303. October 1.

University of Georgia. Southern Regional Water Quality Program. 2005. "Drinking Water Protection in Georgia." Bulletin 1242-5

University of Georgia. 2006. "FACS Cooperative Extension." http://www.fcs.uga.edu/ext/pubs/author.php?pubno=C819-12

Van Every, Lynn R, and SD Dawson. 1995. Groundwater as a vehicle for disease transmission in southeastern Idaho: a case study. *Environmental Health*. Dec. 16-19.

Weir, Erica. 2005. Public Health: Well-water maintenance. *Canadian Medical Association Journal*. 172: 11.

Williams, Amy O. 2007. "Drought boosts well drillers." *McClatchy-Tribune News*. Nov 3.

Wojcick, Don, D Weiss, and G Lindsey. 1996. Cooperative water quality testing and vulnerability factors for private rural wells in central Indiana. *Environmental Health*. April: 16-22.

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