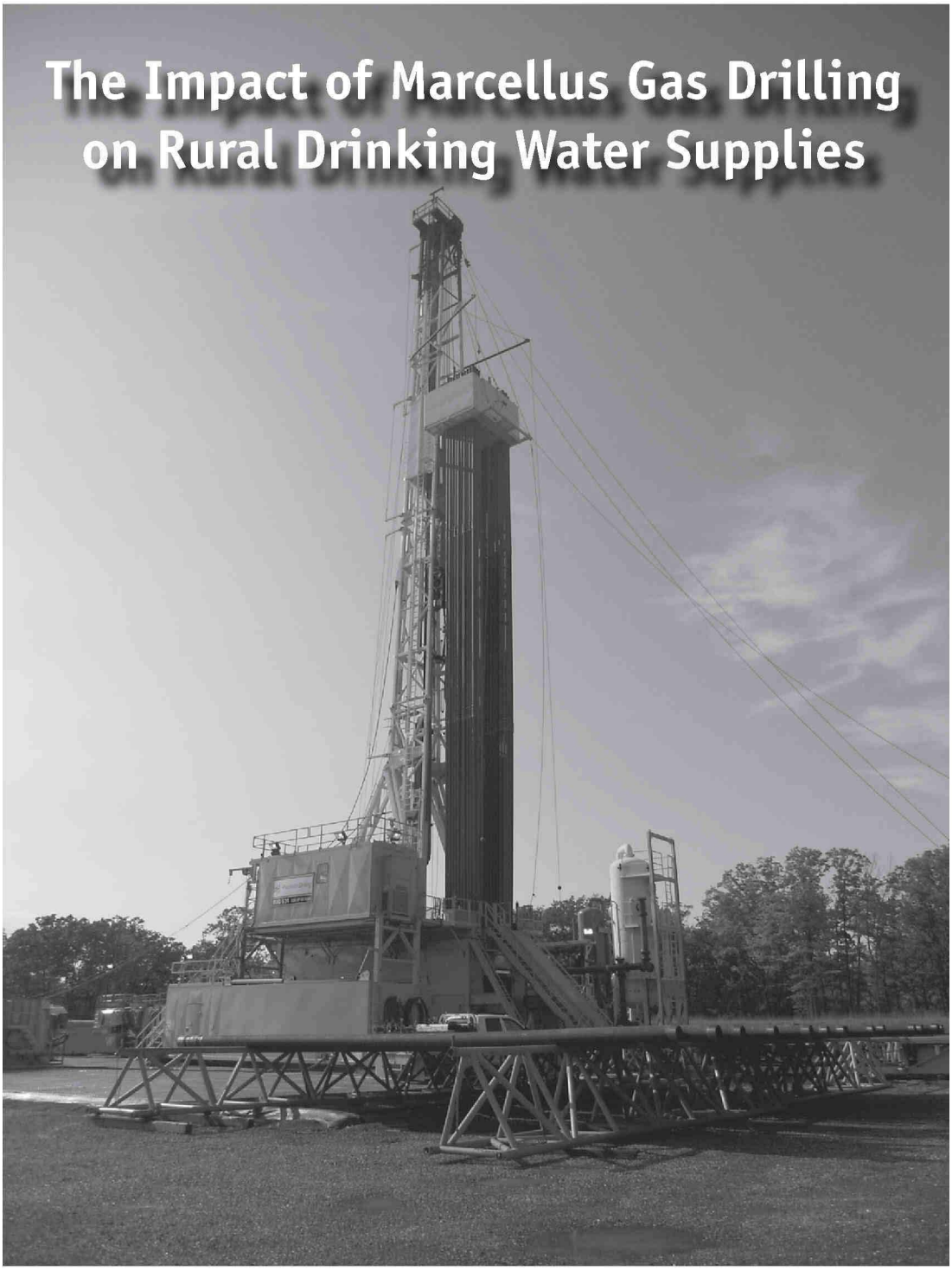
The Impact of Marcellus Gas Drilling on Rural Drinking Water Supplies



The Center for Rural Pennsylvania

A Legislative Agency of the Pennsylvania General Assembly

The Impact of Marcellus Gas Drilling on Rural Drinking Water Supplies

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October 2011

This research was sponsored by a grant from the Center for Rural Pennsylvania, a legislative agency of the Pennsylvania General Assembly.

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Executive Summary

This research looked to provide an unbiased and large-scale study of water quality in private water wells in rural Pennsylvania before and after the drilling of nearby Marcellus Shale gas wells. It also looked to document both the enforcement of existing regulations and the use of voluntary measures by homeowners to protect water supplies.

For the study, the researchers evaluated water sampled from 233 water wells in proximity to Marcellus gas wells in rural regions of Pennsylvania in 2010 and 2011. Among these were treatment sites (water wells sampled before and after gas well drilling nearby) and control sites (water wells sampled though no well drilling occurred nearby).

Phase 1 of the research focused on 48 private water wells located within about 2,500 feet of a nearby Marcellus well pad, and Phase 2 focused on an additional 185 private water wells located within about 5,000 feet of a Marcellus well pad.

During Phase 1, the researchers collected both pre- and post-drilling water well samples and analyzed them for elements of water quality at various analytical labs.

During Phase 2, the researchers or homeowners collected only post-drilling water well samples, which were then analyzed for elements of water quality. The post-drilling analyses were compared with existing records of pre-drilling water quality, which had been previously analyzed at state-accredited labs, from these wells.

According to the study results, approximately 40 percent of the water wells failed at least one Safe Drinking Water Act water quality standard, most frequently for coliform bacteria, turbidity and manganese, before gas well drilling occurred. This existing pollution rate and the general characteristics of the water wells, such as depth and construction, in this study were similar to past studies of private water wells in Pennsylvania.

The study's pre-drilling results for dissolved methane also provided new information that documented its occurrence in about 20 percent of water wells, although levels were generally far below any advisory levels.

Despite an abundance of water testing, many private water well owners had difficulty identifying pre-existing water quality problems in their water supply. The lack of awareness of pre-drilling water quality problems suggests that water well owners would benefit from unbiased and consistent educational programs that explain and answer questions related to complex water test reports.

In this study, statistical analyses of post-drilling versus pre-drilling water chemistry did not suggest major influences from gas well drilling or hydrofracturing (fracking) on nearby water wells, when considering changes in potential pollutants that are most prominent in drilling waste fluids. When comparing dissolved methane concentrations in the 48 water wells that were sampled both before and after drilling (from Phase 1), the research found no statistically significant increases in methane levels after drilling and no significant correlation to distance from drilling. However, the researchers suggest that more intensive research on the occurrence and sources of methane in water wells is needed.

According to the Pennsylvania Oil and Gas Act of 1984, gas well operators are "presumed responsible" for pollution of water supplies within 1,000 feet of their gas well for six months after drilling is completed if no pre-drilling water samples were collected from the private water supply. This has resulted in extensive industry-sponsored pre-drilling testing of most water supplies within 1,000 feet of Marcellus drilling operations. However, the research found a rapid drop-off in testing beyond this distance, which is driven by both the lack of presumed responsibility of the industry and also the cost of testing for homeowners.

The research results also suggest that a standardized list of minimum required testing parameters should be required across all pre-drilling surveys to eliminate many questions and confusion among both water supply owners and water professionals. The results from this study indicate that this standardized list should include bromide among other common parameters.

The research found that bromide levels in some water wells increased after drilling and/or fracking. These increases may suggest more subtle impacts to groundwater and the need for more research. Bromide increases appeared to be mostly related to the drilling process. A small number of water wells also appeared to be affected by disturbances due to drilling as evidenced by sediment and/or metals increases that were noticeable to the water supply owner and confirmed by water testing results.

Increased bromide concentrations in water wells along with sporadic sediment and metals increases were observed within 3,000 feet of Marcellus gas well sites in this study. These results suggest that a 3,000 foot distance between the location of gas wells and nearby private water wells is a more reasonable distance for both presumed responsibility and certified mail notification related to Marcellus gas well drilling than the 1,000 feet that is currently required.

The research found that regulations requiring certified mail notification of water supply owners, chain-of-custody water sampling protocols, and the Pennsylvania Department of Environmental Protection's investigation of water supply complaints were generally followed, with a few exceptions.

However, since voluntary stipulations were not frequently implemented by private water well owners, there may be a greater need for educational or financial resources to help facilitate voluntary testing among well owners.

This research was limited to the study of relatively short-term changes that might occur in water wells near Marcellus gas well sites. Additional monitoring at these sites or other longer-term studies will be needed to provide a more thorough examination of potential water quality problems related to Marcellus gas well drilling.

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Introduction

Pennsylvania has a long history of oil and gas well drilling dating back to the first well in 1859 in Venango County. Since that time, more than 350,000 oil and gas wells have been drilled in the state (Pennsylvania Department of Environmental Protection, 2011a). Until recently, most gas well drilling has occurred in relatively shallow formations in western Pennsylvania as well as some deeper formations, such as the Oriskany Formation, using traditional vertical wells. The advent of horizontal drilling technologies in combination with hydraulic fracturing (also known as hydrofracturing or fracking) has allowed gas drilling companies to explore previously untapped and deeper gas reserves, such as the Marcellus Shale Formation that underlies approximately two thirds of the state (Weidner, 2008) and has demonstrated high production potentials to supply natural gas.

Horizontal wells in the Marcellus differ from traditional vertical wells in the large amount of water used and wastewater produced and the use of chemical additives in fracking to facilitate natural gas release from the rock. Fracking, which uses several million gallons of water along with proppants (typically sand) and various chemical additives (Arthur et al., 2008), has recently received significant public scrutiny. This is due, in part, to concerns about the potential for water supply pollution from the chemical additives, which are not currently regulated by the U.S. Environmental Protection Agency under the federal Safe Drinking Water Act (U.S. Environmental Protection Agency, 2004). The Pennsylvania Department of Environmental Protection (DEP) requires limited disclosure of chemicals used for fracking during the permitting process and some drilling companies have voluntarily provided more detailed information (DEP, 2011b). Further, gas well drilling is regulated by the Oil and Gas Act of 1984, which regulates the permitting, construction and abandonment of gas wells drilled throughout the state.

Marcellus gas wells generate large volumes of waste fluids from fracking fluids returning to the surface ("flowback" fluids) along with naturally occurring deep brine water. The wastewaters typically have a high level of total dissolved solids (TDS) due to the variety and concentration of many different constituents such as chloride, sodium, barium, strontium and iron (Hayes, 2009). The concentration of many water quality parameters in various types of gas drilling flowback fluids and wastewaters reported by Hayes (2009) are substantially above levels considered safe for drinking water. As a result, even small amounts of pollution from improperly constructed wells, inadequate waste storage, or spills can impact nearby water supplies.

Gas well drilling and storage fields have also been implicated in cases of methane migration into shallow groundwater aquifers (Breen et al., 2007; and Buckwalter and Moore, 2007). Methane gas dissolved in water presents an explosion hazard as it escapes from the water into confined household spaces (Keech and Gaber, 1982). There have been reported instances of methane gas migrating from drinking water wells into homes or seasonal camps resulting in explosions (Pittsburgh Geological Society, 2009; and Gough and Waite, 1990) including an occurrence near Dimock, Pa., that was related to Marcellus drilling activity (DEP, 2009). A recent study in northeastern Pennsylvania also found increased concentrations of dissolved methane in shallow groundwater wells close to Marcellus gas well sites (Osborn et al., 2011). The incidence of pre-drilling background concentrations of dissolved methane from natural sources or historical gas drilling has not been intensively studied or documented throughout Pennsylvania prior to Marcellus natural gas drilling operations. However, many domestic wells are now being sampled as part of pre-drilling surveys.

In most of the counties where Marcellus gas drilling is occurring or is projected to occur, more than 30 percent of county residents rely on shallow groundwater wells and springs for their drinking water (U.S. Census Bureau, 1990[1]). Current regulations to protect these water supplies from gas drilling operations are part of the 1984 Oil and Gas Act - Act 223 (Commonwealth of Pennsylvania, 1984) including:

1. Data documenting private water supplies in Pennsylvania was last collected during the 1990 U.S. Census.

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- Mail notification of water supply owners within 1,000 feet of a proposed gas well.
- A minimum separation distance (setback) between gas wells and drinking water wells and springs of 200 feet.
- Gas well operators are presumed responsible for pollution of water supplies within 1,000 feet of their gas well for six months after drilling is completed if no pre-drilling water samples were collected from the private water supply. Gas well operators typically test water supplies within this distance before drilling using a state-accredited water testing laboratory to document pre-existing water quality problems. To be legally valid, these water tests must be collected by an employee or professional consultant working for a state accredited water testing laboratory (called "third party" or "chain-of-custody" testing).
- Layers of casing and cement are installed from the surface to below freshwater zones (called the *fresh groundwater protection string)* to protect groundwater from the drilling process. Regulations were added in February 2011 to strengthen casing and cementing requirements for Marcellus gas wells.
- Waste fluids must be collected in specified pits or tanks to protect water resources.

Enforcement of these regulations in Pennsylvania is the responsibility of DEP's Bureau of Oil and Gas Management (BOGM). BOGM enforcement to protect water supplies focuses on 1) review of permits to ensure notification of water supply owners, 2) inspection of sites to validate proper well construction and wastewater handling and 3) investigation of complaints received by the public related to gas drilling activity. The Oil and Gas Act requires BOGM to investigate potential water supply pollution problems within 10 days after receiving a complaint. Beyond state regulations, water supply owners can take additional voluntary measures (water testing, leasing stipulations, etc.) to protect their water supply. However, anecdotal information from educational workshops provided by the researchers found that most water supply owners relied largely on state regulations.

Previous research has shown that more than 40 percent of private water wells in Pennsylvania fail to meet federal drinking water standards and the lack of statewide water well construction and location standards makes them more susceptible to various sources of pollution (Swistock et al., 2009). Marcellus gas well drilling has increased concern among water supply owners based on various, often contradictory, research reports from Pennsylvania and other states (Osborn et al., 2011; Lustgarten, 2008; Thyne, 2008; Griffiths, 2007; and Gorody et al., 2005). While public concern about potential impacts of Marcellus gas drilling on drinking water wells is persistent, the actual occurrence of problems based on a large-scale and unbiased study is lacking.

Goals and Objectives

The primary goal of this research was to conduct an unbiased and large scale study of water quality in private water wells both before and after the drilling of Marcellus gas wells nearby, providing baseline data on a set of water quality parameters and allowing consideration of potential indicators of groundwater pollution from drilling-related activities. Additionally, the research sought to document the status of both the enforcement of existing regulations and the use of voluntary measures by homeowners to protect water supplies in close proximity to gas drilling sites.

Methodology

The research sampled a total of 233 private water wells near active Marcellus gas wells. The water wells were located in 20 counties throughout the region of Pennsylvania underlain by Marcellus Shale and were part of two distinct phases of the project:

- Phase 1 – both pre- and post-drilling water samples were collected by research staff from 48 private water wells located within approximately 2,500 feet downhill or at gradient to a nearby Marcellus well pad.
- Phase 2 – post-drilling water samples collected by research staff or the homeowner (after training) were compared to pre-drilling data largely collected by professionals working for state accredited water labs hired by gas drilling companies or the homeowner for 185 water wells located within approximately 5,000 feet of a completed Marcellus gas well site.

Phase 1

Phase 1 of the study focused on sampling 49 water wells. These samples were collected by research staff both pre- and post-drilling of a Marcellus gas well nearby, for analysis of a range of water quality parameters. Research staff each identified water wells that met the following criteria:

- Water well was located within approximately 2,500 feet of a Marcellus drilling site where a pad existed.
- The Marcellus pad was at the same elevation or above the water well location.
- Drilling and fracking were expected to occur at each pad site during 2010.
- No more than three water wells could be selected around a given Marcellus gas well pad.

Candidate water wells were initially determined from news and website releases, personal knowledge of regional drilling by each of the researchers, and email contact with water supply owners that participated in various Penn State educational workshops in 2008. As such, they do not represent random samples.

Potential study sites were scrutinized using DEP's eFacts permit system (http://www.dep.state.pa.us/dep/efacts/) and Google Earth to confirm that they met the location, distance and elevation requirements listed above.

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Attempts were also made to equally distribute the water wells in distance categories (0 to 500', 500 to 1,000' etc.) from the Marcellus drilling site and to represent as many Marcellus drilling companies as possible.

Based on these criteria, 49 water well sites were initially selected for sampling between February and September 2010. One site was eventually removed from the study at the request of the water well owner resulting in 48 final water well sites representing 32 separate Marcellus drilling sites operated by 15 different drilling companies.

The researchers made an initial site visit to each of the 48 sites before Marcellus gas well drilling began. The researchers collected water supply information (GPS location, water well depth, age, construction, treatment, etc.) and provided a fact sheet to each water supply owner describing current state regulations and permit requirements related to Marcellus gas drilling. The researchers distributed the fact sheet information to allow the water supply owner to later determine if all state requirements were followed throughout the drilling process.

The researchers inspected the water supply to determine a location to collect untreated water. Where treatment equipment (such as water softeners, ultraviolet lights, and carbon filters) existed, water was collected from the pressure tank or an untreated outside spigot (26 of 48 sites). Where treatment equipment did not exist, water samples were collected from the kitchen faucet (22 of 48 sites). The water system was purged for several minutes as determined by a constant water temperature. Water samples were collected, stored on ice and delivered in person or via overnight mail to three laboratories using sample bottles supplied by each lab.

The researchers analyzed a number of parameters of water quality that may be useful indicators of groundwater pollution from Marcellus wastewaters because they are found at high concentrations in Marcellus wastewaters in comparison to natural groundwater levels and drinking water standards (See Table 1). A large separation in concentrations between gas drilling waste fluids and typical groundwater concentrations allows for a greater likelihood of detection of changes due to pollution. The pre-drilling records of water quality available from other sources for the Phase 2 water wells provided information on additional elements of water quality from which the researchers synthesized the results (See Table 3 on Page 12).

Three different water testing laboratories analyzed the water well samples from this project. Specific analyses conducted by each lab are described below:

- Pennsylvania State University, Agricultural Analytical Laboratory (AAL), DEP certification # 14 00588, conducted analyses of inorganic constituents including pH, total dissolved solids (TDS), total suspended solids (TSS), barium, chloride, hardness (calcium and magnesium), iron, manganese, sodium, strontium, nitrate, and sulfate. Samples for inorganic analyses were collected in one liter, high-density polyethylene bottles that had been pre-cleaned then triple-rinsed during sampling. Lab analyses for each parameter followed standard methods specified by the U.S. Environmental Protection Agency (2009).
- Seewald Laboratories (SL), DEP certification #41 00034, conducted analyses of dissolved methane (in water), oil and grease, and bromide using methods approved by the U.S. Environmental Protection Agency (2009). Samples for methane analysis were collected in three 40 mL glass vials by reducing water flow to a small stream and completely filling each sample to ensure no air space. Laboratory analysis followed DEP's Bureau of Laboratories methane/ethane methodology (DEP, 2011c).

Table 1. Water quality parameters measured in Phase 1 water wells in comparison to Pennsylvania drinking water standards and to typical concentrations in Pennsylvania water wells and Marcellus wastewaters. All concentrations are reported in units of mg/L except pH.

Parameter	Drinking Water Standard[1]	Approximate Median Concentration in Typical Pennsylvania Groundwater[2]	Approximate Median Concentration in Typical Marcellus Wastewater[3]
pH	6.5 to 8.5	7.50	6.60
Total Dissolved Solids	< 500	163.0	67,300
Total Suspended Solids	-	1.0	99.0
Barium	< 2.0	0.070	686
Iron	< 0.30	0.20	39
Manganese	< 0.05	0.01	2.63
Sodium	-	6.87	18,000
Hardness	-	86.1	17,700
Strontium	-	0.26	1,080
Chloride	< 250	5.3	41,850
Sulfate	< 250	18.0	2.4 to 106
Nitrate-Nitrogen	< 10	0.50	0.1 to 1.2
Bromide	-	0.016	445
Dissolved Organic Carbon	-	<1.0	62.8
Dissolved Methane		No data available	No data available
Oil & Grease	-	<5.0	6.3

[1] Pennsylvania Department of Environmental Protection, 2006. [2] Pennsylvania State University, 2011; Davis et al., 2004; and Thurman, 1985. [3] Hayes, 2009.

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- Pennsylvania State University, School of Forest Resources water quality laboratory conducted analyses of dissolved organic carbon, dissolved inorganic carbon, and total dissolved nitrogen. Samples for these analyses were collected in 125 mL amber glass bottles that had been cleaned and burned at 450° C, and were analyzed using the method of high-temperature catalytic oxidation as described by the U.S. Geological Survey (Bird et al. 2003).

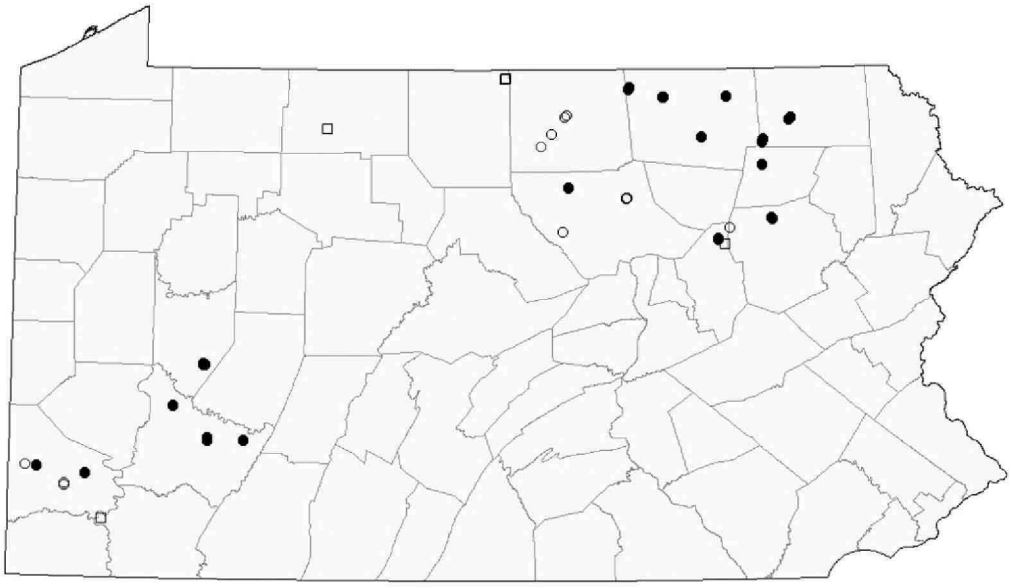
In addition to collecting water supply information and water samples, the researchers also provided each private water well owner with a simple Oakton® TDSTestr11 total dissolved solids (TDS) meter during the initial site visit. TDS measures can be used to monitor for potential pollution by gas drilling wastewaters because the difference between typical groundwater TDS levels and gas drilling wastewater TDS concentrations is large (See Table 1) and TDS is easily measured with very simple meters. Each water well owner was trained on the use and calibration of the TDS meter and provided with a form to record TDS reading from his/her water supply. The well owners were instructed to contact the researchers if the TDS reading increased by more than 50 mg/L on subsequent readings or if they noticed any other obvious changes in their water during drilling or fracking operations. Increases exceeding 50 mg/L, in conjunction with nearby drilling or fracking, were first troubleshot by the researchers to rule out meter problems. When meter problems were ruled out, the researchers revisited the home to confirm the TDS increase and collect another water sample to document any changes in water quality. Collection of samples in response to unexplained TDS increases was necessary at three Phase 1 sites during the study.

The researchers maintained communication with the study participants to determine when drilling and fracking had occurred at the nearby Marcellus gas well site. Once the researchers were notified that fracking had occurred, they arranged for a visit to collect a post-drilling water sample for comparison to the pre-drilling results. Fracking dates were later confirmed from well completion reports in the Pennsylvania Department of Conservation and Natural Resources' (DCNR) PA*IRIS database where possible. All of the Phase I water well sites were sampled within eight months after fracking of the nearby Marcellus gas well (74 percent were sampled within 70 days after fracking). Thus, Phase 1 focused entirely on documenting the potential for relatively short-term changes in water quality after drilling and fracking. This short timeline was necessary because of the study timeline.

During the final site visit, water supply owners completed a short survey to document their overall experiences with the drilling process. Water supply owners received results from all testing including interpretation of results within approximately eight weeks after samples were collected.

Phase 1 sites were monitored for up to 16 months from the start of the project to allow time for drilling and hydrofracturing to occur at each site. Drilling and fracking only was completed on 26 of the 48 sites by the time the research was completed. These are denoted as "fracked sites" in Figure 1. Drilling without fracking occurred at 16 sites, denoted as "drilled sites" in Figure 1. No activity occurred at six sites, denoted as "control sites" in Figure 1. For statistical purposes, the Phase 1 water wells were separated into two treatments (drilled+fracked and drilled only) and control (no drilling or fracking).

Figure 1. Location of the 48 water wells sampled in Pennsylvania during Phase 1. Hollow squares are Control sites (that were not drilled); hollow circles are treatment sites that were Drilled (but not fracked); and closed circles are treatment sites that were drilled then Fracked. Some points represent two or three water wells because of close proximity.



Phase 2

Phase 2 included a broader survey of 185 water wells (205 water wells were sampled but 20 were later determined to be ineligible). These samples were collected by research staff or the homeowner (after training) for analysis of a suite of water quality parameters, and were compared to pre-drilling data generally collected by professionals working with state-accredited

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water testing labs hired by the gas drilling company or the homeowner. To be eligible for Phase 2, homeowners had to meet all of the following criteria:

- Own a private water well that supplied water for their home, farm or camp.
- The water well had to be located within approximately one mile (~5,000 feet) of a Marcellus well site where the gas well was both drilled and fracked.
- The water supply owner had to supply a copy of a pre-drilling water test for comparison to post-drilling results collected by the researchers.

Water supply owners had to allow the researchers to visit their home to collect a post-drilling water sample or they had to attend a workshop to learn proper methods to collect water samples, receive proper sample containers, and drop off water samples at a central location for the researchers to deliver to the water testing labs.

For the samples collected during this project, all parameters measured on Phase 1 water wells (Table 1) were also measured on Phase 2 water wells with the exception of methane, bromide and oil/grease. These three parameters were not included in Phase 2 primarily due to cost limitations and, in the case of methane, difficult sample collection protocols for homeowners. All Phase 2 water quality analyses were conducted by the Agricultural Analytical Services Lab at Penn State University, except dissolved organic carbon and total nitrogen, which were analyzed by the water quality lab of the School of Forest Resources at Penn State University.

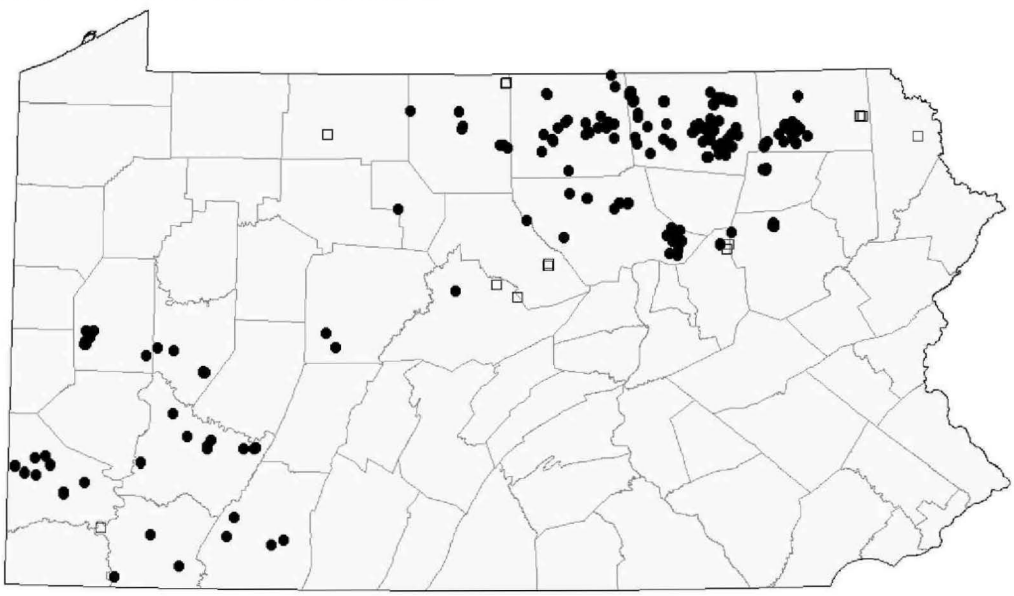
The researchers created a web-based survey to help identify potential participants for Phase 2. They also presented 13 workshops to more than 1,000 private water supply owners interested in participating in the study. Publicity at workshops and through news releases resulted in more than 600 responses to the web-based survey. Two prominent water-testing labs also mailed letters to 762 clients in an attempt to recruit additional participants. While the researchers received interest from hundreds of potential participants, most did not meet at least one of the eligibility requirements listed above. Ultimately, more than 90 percent of the eligible participants who had contacted the researchers by April 2011 were included in the study.

Water supply owners who attended a workshop and met the eligibility requirements were given pre-cleaned sample containers and detailed sample collection instruction. Homeowners then returned home and collected untreated water samples the following morning. They returned samples to a central location where the researchers collected the samples and returned them to Penn State University water labs. Collection of water samples for the Phase 2 parameters was relatively easy, making homeowner collection less prone to sampling errors. Sampling instructions, including how to select a sampling location for untreated water, were covered in detail with each homeowner. Water supply owners responding to the web-based surveys were contacted by one of the researchers to ensure eligibility before visiting their home to collect post-drilling samples. Of the 185 water wells sampled as part of Phase 2, 105 (57 percent) were collected by the researchers while 80 (43 percent) were collected by the water supply owner.

All water supply owners in Phase 2 were given a survey to provide water supply characteristics, water testing history, gas leasing information and other information. Each participant received results of their post-drilling water test along with a comparison of the results to their pre-drilling tests report within approximately eight weeks after sample collection.

Thirteen water well sites were selected as control sites for Phase 2. These water wells met all of the necessary criteria but they did not have any completed Marcellus gas wells within five miles (about 25,000 feet). Thus, for statistical comparisons, Phase 2 of the project included 172 treatment water wells (completed Marcellus gas well within one mile) and 13 control water wells (no Marcellus gas wells within five miles) (See Figure 2).

Figure 2. Location of the 185 water wells sampled in Pennsylvania during Phase 2. Hollow squares are Control sites (not drilled); closed circles are treatment sites that were drilled then Fracked.



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Statistical Analyses

Staff at the Penn State Statistical Consulting Center conducted the statistical analyses. Data from the two phases of the study were treated independently in statistical analyses. Statistical models were based on differenced data (post-drilling minus pre-drilling concentration) for each water quality parameter. Large variability was observed in the water quality data within time periods (pre- or post-drilling). This was likely due to the large spatial area of sampling across different geologies and land uses, and temporal variability of the sampling across different weather conditions and seasons. Previously, these variables were found to be important in explaining water quality in Pennsylvania groundwater wells (Swistock et al., 2009).

Various transformations of the data (square root, natural log, etc.) were used to make the variability between drilling types more uniform. Mixed Analysis of Variance (ANOVA) and regression models were used to test for the effect of drilling and fracking influences (Phase 2) or varying treatments (drilling and drilling+fracking in Phase 1) in comparison to control sites. The distance between the water well and gas well was also included in statistical models. Statistical significance was evaluated at the 95 percent confidence level.

Data Quality Assurance and Control

To ensure the reliability of water quality data, 18 quality control samples, representing approximately 6 percent of the total number of water samples, were submitted to the water testing labs during this study. These 18 quality control samples included nine duplicate samples and nine blanks (explained below). These samples were labeled identically to those from private wells and were submitted to the laboratory among other samples from private wells. The purpose of these samples was to measure how precise and repeatable the water quality results were from the laboratory. The types of quality control samples submitted to the lab are described below along with a summary of the laboratory performance shown in Table 2. Overall, the results from the quality control samples indicate that water quality data collected during this study were of excellent quality.

Duplicate samples were comprised of two samples from the same well that were blindly submitted to the labs to measure the repeatability of their results. Nine well samples were randomly selected throughout the study to be duplicated. Table 2 reports the average percent difference between duplicate sample results. Quality control guidelines suggest that the percent difference between duplicate samples should be less than 25 percent to consider lab results precise (Cavanagh et al., 1998) and all parameters met this criterion.

Blank samples are distilled water that contained levels of each parameter below detection. These samples measured the accuracy of the water laboratory in detecting very low concentrations. A total of nine blanks were submitted to the water laboratory throughout the project, each disguised as a private well sample. Quality control criteria suggest that no more than 5 percent of blank samples should exceed the detection level. All blank samples produced results below detection for all parameters in this study.

Results

Water Well Characteristics

Pennsylvania is one of just two states nationwide that lack statewide standards for construction of private water wells. A previous study funded by the Center for Rural Pennsylvania reported on characteristics of water well construction in a two-year survey of 701 wells throughout the state (Swistock et al., 2009). Water well construction among the 233 wells in this study mirror the results of the larger 2009 study.

Two percent of the 233 water wells were hand-dug wells while 13 percent were drilled wells with no visible casing above ground and 85 percent were drilled wells with a visible metal or plastic casing above ground.

Only 20 percent of the study wells had a sanitary well cap and an obvious grout seal existed on only 8 percent (evaluated on Phase 1 wells only).

The depth of water wells in this study ranged from 25 feet (hand dug well) to 660 feet with a median depth of

Table 2. Results of quality control samples analyzed during the study. Duplicate sample values report the average percent difference between two measurements from the same sample. Blank sample values report the percent of blank samples that were measured above the detection limit.

Parameter	Duplicate Samples	Blank Samples
pH	1.0 percent	n/a
Total Dissolved Solids	4.5 percent	0 percent
Total Suspended Solids	21.2 percent	0 percent
Barium	1.5 percent	0 percent
Iron	3.4 percent	0 percent
Manganese	0.1 percent	0 percent
Sodium	2.6 percent	0 percent
Hardness	1.5 percent	0 percent
Strontium	0.9 percent	0 percent
Chloride	5.3 percent	0 percent
Sulfate	12.2 percent	0 percent
Nitrate-Nitrogen	1.4 percent	0 percent
Bromide	0 percent	0 percent
Dissolved Organic Carbon	7.8 percent	0 percent
Dissolved Methane	1.4 percent	0 percent
Oil & Grease	0 percent	0 percent

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178 feet. Most well owners (89 percent) reported that their well had never run out of water.

More than 80 percent of the water wells tested were constructed since 1970 although a few dated back to before 1900 (hand dug wells).

Half of the water wells had at least one water treatment device installed. The most common treatment devices were sediment filters (27 percent) and water softeners (24 percent).

Pre-Drilling Water Testing

The 1984 Pennsylvania Oil and Gas Act includes presumed responsibility for water quality problems occurring in water supplies within six months of drilling a gas well where the water supply is within 1,000 feet of a gas well site. One defense against this liability presumption is for gas well operators to produce pre-drilling water test results that are collected by an independent third party and analyzed by a state-accredited water laboratory. Industry sponsored pre-drilling water testing occurred on 64 percent of the water wells in this study. More than 90 percent of water wells within 1,000 feet of a Marcellus site were included in pre-drill testing funded by the respective gas drilling company. Industry pre-drill water testing decreased to about 41 percent of water wells at distances beyond 3,000 feet from the Marcellus well site and industry pre-drill testing was rare (10 percent) at distances over 5,000 feet. Water testing purchased by gas drilling companies was usually more comprehensive than homeowner testing, typically covering 15 or more parameters. Currently, there is no standard list of parameters for which the companies must test. The most common parameters tested by the industry were pH, total dissolved solids, total suspended solids, chloride, barium, magnesium, and methane. All of these parameters were analyzed in more than 90 percent of the pre-drilling samples paid for by drilling companies.

If gas drilling companies expect to use pre-drilling testing for defense against presumed responsibility, they are required under the Oil and Gas Act to use chain-of-custody testing protocols where independent consultants or lab employees collect and deliver the samples to state accredited water testing labs. While all industry-sponsored pre-drill water tests in this study were analyzed by state accredited water labs, water supply owners indicated that 6 percent of these samples were collected by an employee of the gas drilling company. Eighty-eight percent indicated that the samples were properly collected by an employee of the lab or a consultant while 6 percent were unsure who collected their water sample.

Results from industry-sponsored pre-drill testing are typically first sent to the gas drilling company. Water supply owners are entitled to a free copy of water tests conducted on their water supply but the time to receive these results varied considerably. About 8 percent of water supply owners responded that they never received their pre-drilling test results while those that did receive results waited an average of about eight weeks, although some waited more than 2 years.

Even though 64 percent of water supply owners in this study received pre-drill water testing by the gas drilling company, 59 percent still decided to pay for their own pre-drilling water test. In fact, 28 percent of water supply owners had both types of pre-drilling water testing done indicating some level of distrust of water testing paid for by the gas drilling companies. Homeowner testing tended to be less comprehensive than testing done by gas drilling companies but still had a median cost of $353 (range $30 to $1,640 per sample). Cost was clearly a major hurdle to comprehensive pre-drilling water testing among many water supply owners. When asked how much they were willing and able to pay for pre-drilling water testing (assuming no other testing would be done for them), 53 percent of the private water well owners in this study indicated $400 was the maximum they could afford (19 percent indicated $200 was the most they could afford). Only 18 percent were willing to pay more than $800 for comprehensive water testing.

Given that many water supply owners were unwilling or unable to pay for comprehensive pre-drilling water testing, they had to rely on various sources to prioritize what parameters they would pay to have tested. About two-thirds relied heavily on testing packages recommended by various state accredited water testing labs while 32 percent used Penn State Extension guidelines for recommended testing. Much smaller percentages (<10 percent) indicated they used recommendations from DEP, industry or other academic institutions for the water testing parameters.

A summary of results from pre-drilling water samples is provided in Table 3 on Page 12. These data include pre-drilling samples from water wells in both phases of this project (total = 233 water wells). Further, the results include both parameters measured on water well samples collected during both phases of this study (see Table 1) and additional parameters synthesized from the pre-drilling records of water quality available from other sources for the Phase 2 water wells. Multiple pre-drilling water test results were available for 30 (16 percent) of the Phase 2 water wells. In this case, preference was given first to independently collected chain-of-custody (COC) samples. Where multiple COC samples were provided, results closer in time to the beginning of gas well drilling and/or results with a more comprehensive list of parameters were selected to represent the pre-drilling conditions. Eighty-eight percent of the pre-drilling water samples were collected in 2009 or 2010 using collectively more than 30 state accredited water labs. Of the 233 water wells in this study, pre-drilling water samples collected using proper COC procedures were available for 219 (94 percent). A breakdown of the sources of pre-drilling water tests shown in Table 3 include:

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Table 3. Water quality results from sampling 233 private water wells before Marcellus gas well drilling occurred nearby. Not all parameters were analyzed on each water well sample as indicated by the number of samples. All units are mg/L unless otherwise noted.

Parameter	Samples	Median	Minimum	Maximum	Drinking Water Standard[1]	Percent Failing Standard
pH (pH units)	233	7.44	5.08	9.24	6.5 - 8.5	17
Total Dissolved Solids	233	190	26	1,448	500	3
Chloride	226	5.9	0.42	371	250	<1
Iron	222	0.05	<0.0025	20.46	0.30	20
Barium	218	0.13	<0.001	7.38	2.0	1
Sodium	200	10.89	0.27	480.0	-	-
Manganese	203	0.01	<0.001	6.64	0.05	27
Total Suspended Solids	197	2.5	<1.0	62.3	-	-
Hardness	191	116.9	0.857	707.0	-	-
Dissolved Methane	189	0.01	0.00011	58.30	-	-
Sulfate	177	14.0	<0.10	441.0	250	<1
Oil & Grease	170	<5.0	<5.0	<6.80	-	-
Magnesium	140	6.98	<0.10	70.0	-	-
Strontium	136	0.28	<0.001	3.51	-	-
Alkalinity	132	141.5	6	403	-	-
Calcium	130	36.16	0.26	220.8	-	-
MBAS - Surfactants	119	<0.5	<0.05	0.186	0.50	0
Coliform Bacteria	125	<1	<1	>201	<1	33
Arsenic	115	0.0025	<0.0005	0.0277	0.01	4
Fecal Coliform Bacteria	122	<1	<1	>201	<1	8
Potassium	107	1.27	<0.5	4.06	-	-
Turbidity (NTU units)	102	<1	<1	21.20	1.0	32
Lead	104	0.0025	<0.0001	0.325	0.015	7
BTEX[2]	95	All below detection			0.005 - 10	0
Nitrate-Nitrogen	88	<0.50	<0.04	9.0	10	0
Dissolved Organic Carbon	71	0.39	0.05	1.61	-	-
Chromium	67	<0.005	<0.001	0.0055	0.10	0
Cadmium	67	<0.001	<0.0005	0.0025	0.005	0
Selenium	67	<0.005	<0.0005	0.0038	0.05	0
Mercury	61	All below detection (<0.0002)			0.002	0
Silver	60	All below detection (<0.0005)			0.10	0
Bromide	56	<0.10	<0.02	0.022	-	-
Total Dissolved Nitrogen	55	0.56	0.02	9.12	-	-
Sulfide	35	<0.05	0.009	0.50	-	-
Gross alpha (pCi/L)	21	1.17	<0.001	3.20	15	0
Radium 226 (pCi/L)	13	0.16	<0.001	0.61	5	0
Radium 228 (pCi/L)	12	0.145	<0.001	1.32	5	0
Radon (pCi/L)	12	775.1	112	3979	-	-

[1]Pennsylvania Department of Environmental Protection (2006). [2]BTEX = benzene, ethylbenzene, toluene and xylene.

- 48 COC samples collected by the researchers (Phase 1 sites).
- 90 COC samples collected by labs or consultants hired by gas companies to conduct pre-drilling testing.
- 81 COC samples collected by labs or consultants hired by the water supply owner to conduct pre-drilling testing.
- 14 samples collected by the water supply owner and delivered to a state accredited water testing lab.

Approximately 40 percent of the water wells included in this study had at least one pre-existing water quality problem. The most frequent parameter to exceed state safe drinking water standards was coliform bacteria, although impairments for turbidity and manganese were also common. The pre-drilling water quality results shown in Table 3 are very similar to various surveys conducted in Pennsylvania over the past several decades (Swistock et al., 2009; Lindsey et al., 2002; Bickford et al., 1996; Swistock et al., 1993; Sharpe et al., 1985; and Francis et al., 1982).

Swistock et al. (2009) found that awareness of water quality problems in private water wells in Pennsylvania was extremely low (<30 percent) among water supply owners, and surmised that a lack of comprehensive testing was responsible for the low awareness of problems among water supply owners.

Results from this study, however, suggest that the availability of comprehensive water quality testing data does not necessarily result in much greater awareness of pre-drilling water quality problems. For example, only about 30 percent of homeowners with water supplies that failed drinking water standards for pH or total coliform bacteria were able to identify these on the study survey as pre-existing problems in their water supply. It appears more likely that the cause for low awareness is related to an inability to interpret the meaning of results shown on water test reports.

Seventy-five percent of water supply owners in this study indicated that their water test reports were either somewhat or very difficult to interpret. A lack of understanding of water test reports results in reduced awareness of important pre-existing water quality problems that could create unsafe drinking water. This lack of understanding also has legal implications since COC

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pre-drilling water test reports can be used as evidence of pre-drilling water quality problems during legal cases that seek to prove damages to water supplies. Water supply owners need to understand what water quality problems are being legally documented before drilling to determine if they agree with these findings or wish to collect their own COC pre-drilling water samples to refute pre-existing problems found in industry-sponsored testing.

Background data on the occurrence of dissolved methane concentrations in private water wells has been lacking in Pennsylvania. Dissolved methane gas was detected in 24 percent of the 189 water wells in this study that were sampled pre-drilling. When dissolved methane was found, it was usually below 1 mg/L (19 percent). Only 2 percent of water wells had pre-drilling methane concentrations above 10 mg/L and 1 percent were above 20 mg/L. Caution should be used in interpreting these dissolved methane results since Phase 2 water well samples were analyzed by multiple laboratories likely using different sampling and analysis methods. Still, dissolved methane was detected in 19 percent of the Phase 1 water wells where consistent sample protocols and one laboratory were used.

Marcellus Drilling Characteristics

The water wells in Phases 1 and 2 were located near 141 Marcellus gas well sites operated by 28 different drilling companies. More than 80 percent of the water supply owners indicated that they were somewhat or very concerned that nearby gas well drilling would impact their water supply. This high level of concern prompted them to seek information about gas drilling in their area most frequently from neighbors, friends, or family members (80 percent). Other sources of Marcellus information used by the water well owners were websites (31 percent), DEP (23 percent), Penn State Extension (22 percent), local government (16 percent), newspaper/radio/TV (14 percent) and drilling companies (11 percent).

Water supply owners in this study controlled 22,043 acres of land in Pennsylvania. Nearly 75 percent of these properties (173 water supplies in this study) had an existing lease for Marcellus gas drilling but only 57 percent of these leases included any stipulations to protect water resources beyond state regulations. Of the 173 water supply owners with leases, the most common water stipulations were:

- A setback between the water supply and the Marcellus well greater than the 200-foot state minimum (included in 32 percent of leases).
- Required pre-drilling water testing regardless of distance from gas well (29 percent of leases).
- Required post-drilling water testing (12 percent of leases).
- Specific requirements on replacement of water supplies impacted by drilling (10 percent of leases).

Other lease stipulations, including testing before seismic activity, measurement of water well flow before drilling, no-surface leases, and access to water on the property, were less common (all occurred in less than 10 percent of leases).

The distances between water wells in Phase 1 and Phase 2 of this project and nearby Marcellus gas wells is shown in Figure 3 (the 13 control wells that were more than 25,000 feet from a Marcellus well are not included in Figure 3). Phase 1 sites focused on water wells generally within 2,500 feet of a gas well while Phase 2 water wells were split into distances occasionally exceeding 5,000 feet from the nearest gas well. Distances were included in statistical models to explore if water quality changes were correlated to gas well locations relative to water well locations.

The Oil and Gas Act includes a provision requiring certified mail notification of water supply owners within 1,000 feet of a proposed gas well site during the permitting process. Information from participants in both phases of this study support that certified mail notification is usually, but not always, received by water supply owners. Of the 54 water supply owners within 1,000 feet of a Marcel-

Figure 3. The number of water wells that were sampled in each phase of this project in relation to their distance from the nearest Marcellus gas well site.

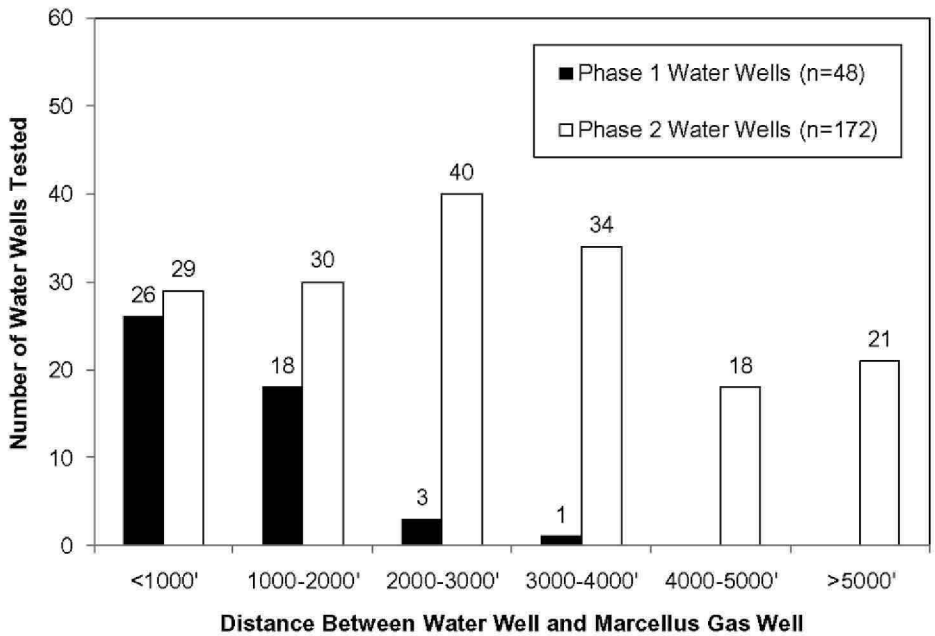

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Figure 4. Comparison of pre-drilling total dissolved solids (TDS) versus post-drilling total dissolved solids concentrations in water wells sampled in both phases of this study. Points above the diagonal dashed line represent water wells where the TDS level was higher in the post-drilling sample in comparison to the pre-drilling sample. Points below the dashed line indicate higher concentrations in the pre-drilling water sample.

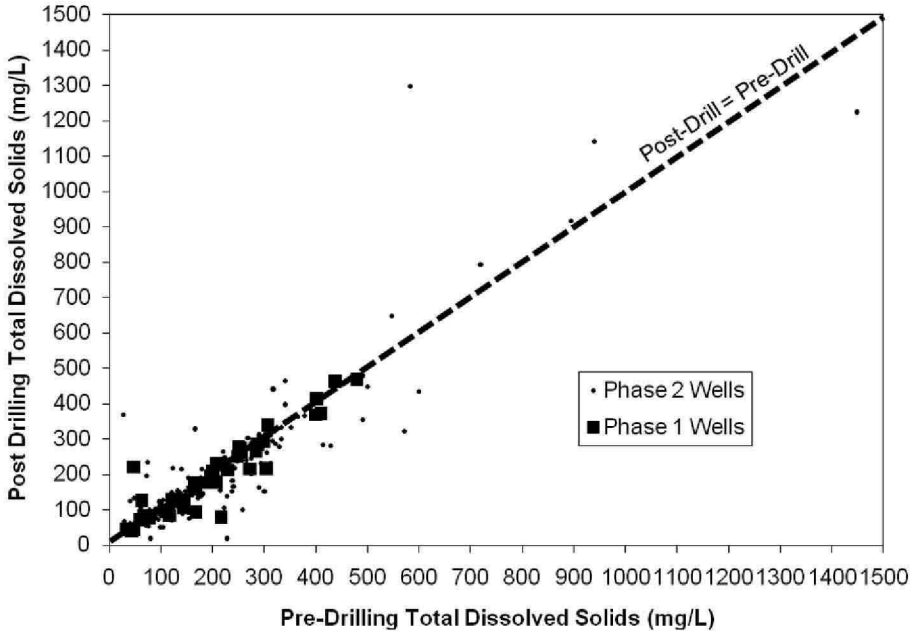
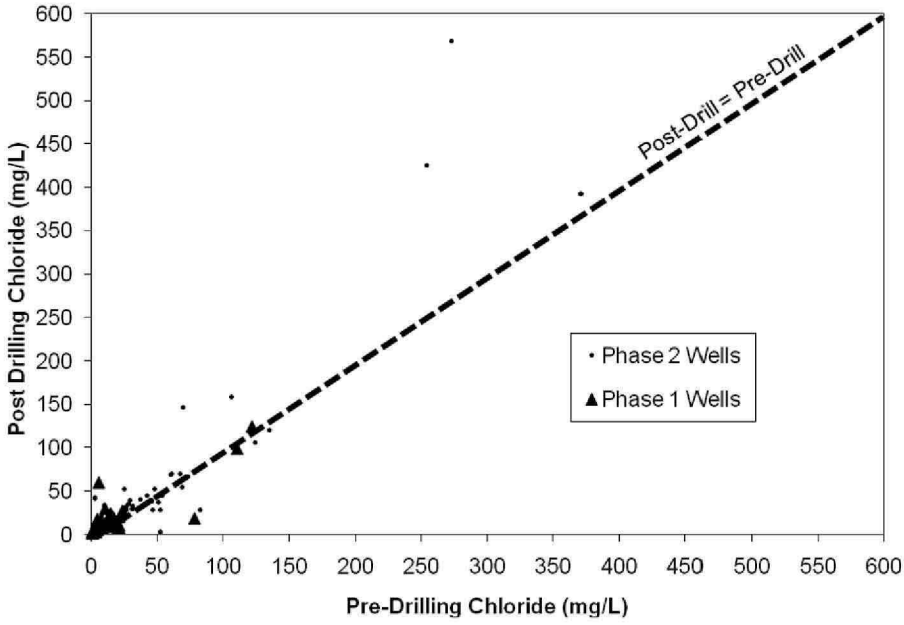


Figure 5. Comparison of pre-drilling chloride versus post-drilling chloride concentrations in water wells sampled in both phases of this study. Points above the diagonal dashed line represent water wells where the chloride level was higher in the post-drilling sample in comparison to the pre-drilling sample. Points below the diagonal dashed line indicate higher concentrations in the pre-drilling water sample.



lus gas well in this study, nine (16 percent) indicated that they never received certified mail notification of the gas well site. Another two participants were unsure if they had received certified mail notification.

The dates when each Marcellus gas well was fracked were determined from well completion reports available through DCNR's PA*IRIS database and visual observations. All of the Phase 1 water well sites were sampled within eight months after fracking of the nearby Marcellus gas well (39 percent were sampled within one month after fracking). Phase 2 sites represented a larger range of elapsed time between fracking and water sample collection ranging from two days to more than 800 days. Sixty-two percent of the Phase 2 water well sites were sampled within six months after fracking of the nearby Marcellus gas well while 83 percent were sampled within 1 year after fracking. Thirty of the Phase 2 water wells (17 percent of the total) were sampled more than 1 year after fracking of the nearby Marcellus gas well and three water wells (2 percent) were tested more than 2 years after fracking occurred.

Overall, the results presented in this report encompass both short-term (Phase 1 focus) and longer-term (Phase 2) impacts that may have occurred due to drilling and/or fracking. Given the relatively recent onset of horizontal drilling and fracking in the Marcellus Formation in Pennsylvania, very few sites are currently available to investigate the potential for extended impacts beyond 2 years.

Post-Drilling Water Quality

Analyses of the data from both Phase 1 and Phase 2 water wells generally showed a lack of statistically significant changes in water quality parameters due to Marcellus drilling or fracking activity

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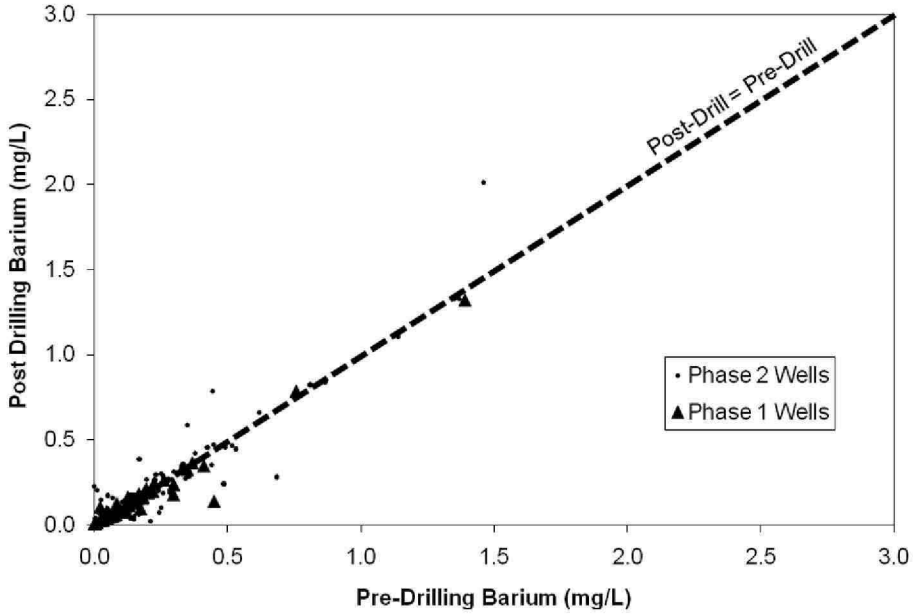
when comparing pre- to post-drilling elements of water quality. These statistical results stem largely from the fact that there was a large degree of variability in each water quality parameter across the wells sampled within a sampling period (pre- or post- drilling) in comparison to any changes that occurred between the two sampling time periods. The high degree of variability in a given element of groundwater quality across the region reflects differences in environmental conditions, such geology and climatic fluctuations, across the Marcellus region.

In some cases, statistical analyses were heavily influenced by a few outlier data points. Although general changes in water quality were not evident, these outliers could, in some cases, suggest sporadic impacts from drilling and/or fracking. Since overall statistically significant changes in water quality were not apparent, results from both Phase 1 and Phase 2 water wells were combined into simple plots of pre-drilling (x-axis) versus post-drilling (y-axis) water chemistry. These graphs illustrate the lack of overall changes in water chemistry after drilling occurred while still allowing further discussion and explanation of outliers that might suggest impacts from drilling activity.

Figure 6. Comparison of pre-drilling barium versus post-drilling barium concentrations in water wells sampled in both phases of this study. Points above the diagonal dashed line represent water wells where the chloride level was higher in the post-drilling sample in comparison to the pre-drilling sample. Points below the diagonal dashed line indicate higher concentrations in the pre-drilling water sample. One value in excess of 4.0 mg/L of barium in a control water well is not shown.



Total dissolved solids, chloride and barium are three of the most commonly used water quality parameters to indicate potential pollution from gas well drilling brines and waste fluids (See Table 3 on Page 12). The high concentration of these parameters in the brines and waste fluids in relation to typical background concentrations in Pennsylvania groundwater make them useful indicators (See Table 1 on Page 7). Figures 4, 5, and 6 show the concentrations of total dissolved solids, chloride and barium in pre-drilling versus post-drilling water samples.

There was generally strong agreement between TDS concentrations in pre- and post-drilling water samples. Most TDS concentrations were between 100 and 400 mg/L in both pre- and post-drilling water samples. In all cases where post-drilling TDS levels exceeded the recommended drinking water standard of 500 mg/L, the pre-drilling TDS level also exceeded 500 mg/L. The few obvious outliers in Figure 4, where post-drilling TDS concentrations increased far above pre-drilling levels, did not appear to be related to gas drilling activity based on other water quality parameters for those samples (chloride, barium, etc.) along with, in some cases, additional pre-drilling samples showing significant natural variability in these water wells.

Trends in chloride between pre- and post-drilling water testing were similar to TDS results (Figure 5). Most post-drilling chloride concentrations were below 100 mg/L. In the few cases where post-drilling chloride concentrations exceeded the recommended drinking water standard of 250 mg/L, pre-drilling concentrations also exceeded the standard. Based on the entire suite of parameters tested on those water wells, it appears that the increased chlorides were related to natural variations and not nearby gas drilling activity. Within the scatter at the low concentrations in Figure 5 is a Phase 1 water well where chloride concentrations increased from 5.9 mg/L to nearly 60 mg/L shortly after the nearby Marcellus gas well was fracked. This water well also had increases in other parameters (sodium, barium, etc.) that did not exceed Safe Drinking Water standards and are further explained in the bromide results section.

Potential increases in barium due to gas well drilling activity would have human health implications since barium has a health related drinking water standard of 2.0 mg/L. Barium in both pre- and post-drilling water samples was generally below 0.5 mg/L (Figure 6). Interestingly, the highest barium concentrations (> 4.0 mg/L) were observed

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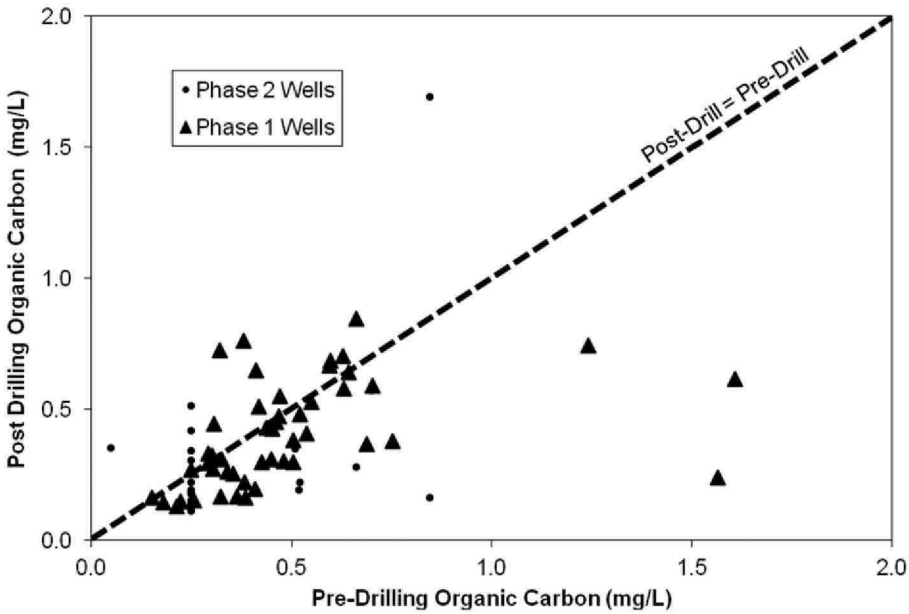
Figure 7. Comparison of pre-drilling dissolved organic carbon (DOC) versus post-drilling DOC concentrations in water wells sampled in both phases of this study. Points above the diagonal dashed line represent water wells where the DOC level was higher in the post-drilling sample in comparison to the pre-drilling sample. Points below the diagonal dashed line indicate higher concentrations in the pre-drilling water sample.



in one of the control water wells. Of the wells located near gas drilling operations, only one had a post-drilling barium concentration in excess of 2.0 mg/L. This water well also had a high barium concentration before drilling (1.4 mg/L). There were no other changes in this water well to suggest gas well drilling fluids so the barium increase appeared to be from natural variability.

Graphs similar to those for TDS, chloride and barium are provided in Appendix I for sulfate, hardness, sodium and strontium. Results for these parameters are similar to those for TDS, chloride and barium showing very similar concentrations of each parameter in pre- and post-drilling water samples from water wells in both phases of this project.

Dissolved organic carbon (DOC) contains a variety of organic compounds and is a measure of the total dissolved organic matter present in natural waters (Thurman, 1985). Significant increases in DOC concentrations could be a useful indicator of the presence of organic chemicals that may be used during fracking activities or that are present in drilling wastewaters. DOC was rarely measured in pre-drilling testing done by the gas drilling industry or by homeowners on Phase 2 water wells, so most comparisons are limited to Phase 1 water wells that were sampled by the researchers. Overall, the results for DOC concentrations both pre- and post- drilling (See Figure 7) are very low in concentration. These are typical levels for naturally occurring dissolved organic materials in ground waters and do not suggest any pollution.

Dissolved Methane

Sporadic reports of increases in dissolved methane in water wells have been reported in Pennsylvania as a result of Marcellus gas drilling. A recent Duke University study further found that dissolved methane concentrations were strongly correlated to the distance from the nearest Marcellus gas well (Osborn et al., 2011). Pre- and post-drilling methane concentrations were tested on the 48 water wells in Phase 1 of this project. Most post-drilling methane levels were generally near or below the detection level (<0.02 mg/L) even after drilling and fracking had occurred (See Figure 8). Dissolved methane did increase at one drilled site but this site also had a moderate level of methane before drilling occurred. Dissolved methane did not increase at fracked sites and was not correlated to the distance to the nearest Marcellus well site.

Bromide

Bromide was rarely tested as part of industry sponsored pre-drilling surveys or voluntary homeowner testing (See Table 3 on Page 12). It was selected as a testing parameter for Phase 1 water wells in this study as a possible indicator of small influences from natural brines or drilling waste fluids because bromide is typically not found in detectable concentrations in undisturbed groundwater (Davis et al., 2004) and because bromide is found in relatively high concentrations in gas drilling wastes (See Table 1 on Page 7).

While bromide was always below the detection level (less than 0.1 mg/L) in pre-drilling samples from the Phase 1 water wells, there were numerous cases where bromide was detected in post-drilling samples (See Figure 9 on Page 18). More than 30 percent (5 of 16) of the water wells in close proximity to drilled sites had detectable concentrations of bromide after drilling occurred and 8 percent (2 of 26) of sites where drilling and fracking occurred had measurable bromide. The seven water wells with increased bromide were all located within 1,670 feet of five different Marcellus well pads operated by three different drilling companies across north-central and northeastern Pennsylvania. None of the control wells had mea-

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sureable bromide during the post-drilling testing. There is no drinking water standard for dissolved bromide so these increased concentrations alone do not represent a direct health concern. However, elevated bromide concentrations can, under certain circumstances, cause the formation of disinfection by products that do have a health-based drinking water standard. So, elevated bromide can create an indirect health issue as it may combine with other elements in water to cause carcinogenic compounds.

Bromide is sometimes used as a drilling mud additive in the drilling process, which could be a potential source of the increased bromide levels in post-drilling water samples. Drilling mud recirculation pits are sometimes used on the well pad, which could account for a localized bromide source. A second potential source would be from flowback water, however this is unlikely because other analyses (TDS, barium, strontium, chlorides) would have indicated increases if a release of flowback water had occurred. Six of the seven wells with a measurable bromide increase did not experience other significant water quality changes. Chloride levels were below detection in both pre- and post-drilling samples in four of the seven wells with measureable bromide increases with small increases occurring in the other three wells. Other parameters, including TDS, barium, sulfate, iron, strontium and sodium had mixed changes in these six water wells. One exception was a Phase 1 water well where an increase in bromide after drilling and fracking was accompanied by increases in numerous other water quality parameters. While these increases were apparent, they did not exceed or closely approach Safe Drinking Water standards. These increases were observed just days after fracking was completed on a Marcellus well approximately 1,400 feet from the water well. Organic carbon levels did not increase in this well after fracking. An additional post-drilling sample was collected from this water well approximately 10 months after fracking, which showed nearly all parameters, including bromide, had nearly returned to pre-drilling concentrations.

Water Supply Complaints

Participants in both phases of the study were asked whether they noticed any obvious changes to their water supply during or after gas well drilling occurred. Those that noticed a change in their water were given space on the survey to explain the change. Responses were categorized by the researchers into broad categories including changes to sediment, metals, odors, dissolved gases, tastes, foaming, water flow and water temperature.

Overall, 33 of the 233 water supply owners (14 percent) felt that some aspect of their water well had changed as a result of nearby gas drilling. Of the 33 water supply owners who perceived changes to their water well quality or quantity, only nine contacted DEP for an investigation. These water wells were all within 3,000 feet of the nearest Marcellus gas well. State regulations require DEP to investigate drinking water complaints within 10 days of receipt. Of the nine water supply owners who contacted DEP, seven (78 percent) indicated that DEP personnel responded within 10 days (three indicated the DEP response was less than two days). Two water supply owners indicated that DEP failed to respond within 10 days. In both cases, these water supply complaints occurred in the early stages of Marcellus development.

It should be noted that there were 11 other water supply owners who indicated that they contacted DEP to inves-

Figure 8. Comparison of pre-drilling dissolved methane versus post-drilling dissolved methane concentrations in 48 water wells sampled in Phase 1. Points above the diagonal dashed line represent water wells where the dissolved methane was higher in the post-drilling sample in comparison to the pre-drilling sample. Points below the diagonal dashed line indicate higher concentrations in the pre-drilling water sample. Symbols denote sites where no drilling occurred (Control), sites where only drilling occurred but no fracking (Drilled) and sites where both drilling and fracking occurred (Fracked).

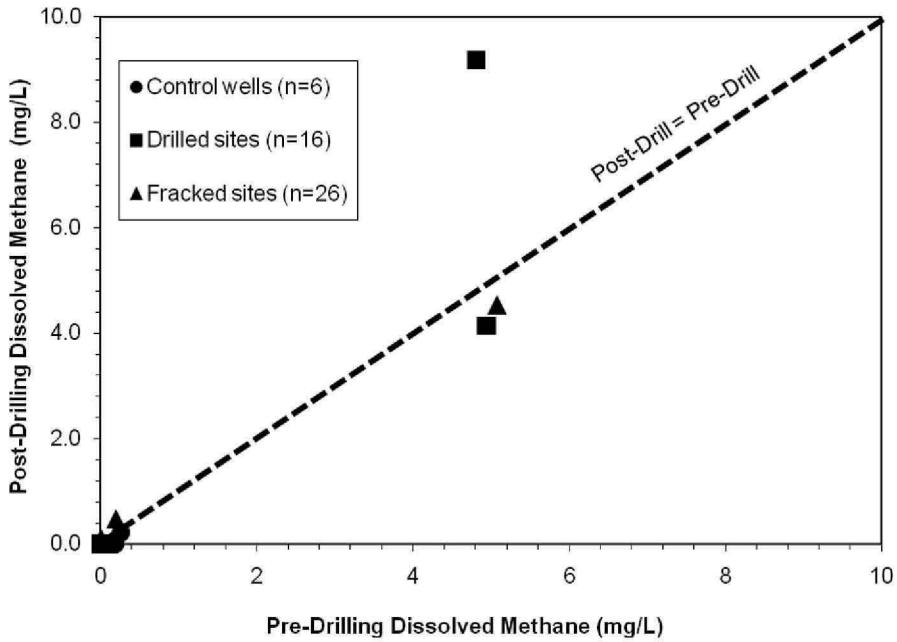

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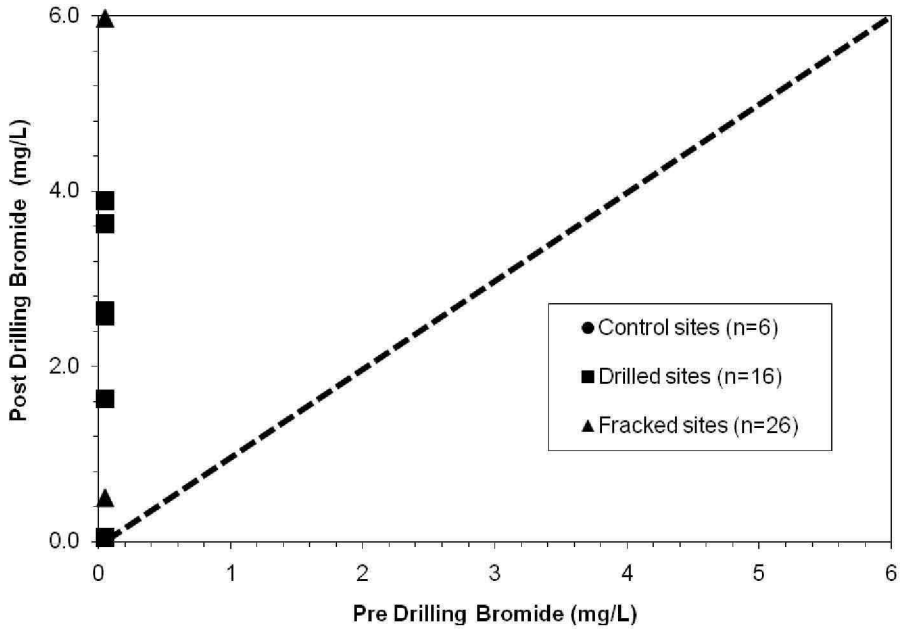
Figure 9. Comparison of pre-drilling bromide versus post-drilling bromide concentrations in water wells sampled in Phase 1. Points above the diagonal dashed line represent water wells where the bromide was higher in the post-drilling sample in comparison to the pre-drilling sample. Points below the diagonal dashed line indicate higher concentrations in the pre-drilling water sample. All pre-drilling bromide concentrations were greater than zero yet less than the detection limit of 0.10 mg/L, with values of ½ the detection limit substituted here as the starting point. Symbols denote sites where no drilling occurred (Control), sites where only drilling occurred but no fracking (Drilled) and sites where both drilling and fracking occurred (Fracked).



tigate other complaints not directly related to their water supply (spills, illegal water withdrawals, etc.). Of those that provided further comment, all indicated that DEP responded to their complaint within 10 days.

Perceived changes to water supplies were more frequent among Phase 2 water well owners (17 percent) presumably because they generally volunteered for this project after drilling had already occurred. Only three Phase 1 water well owners perceived changes to their water supply, which represents 12 percent of the sites where drilling occurred and 7 percent of the sites where fracking occurred.

The number of water supply owners in each phase of the project that perceived various changes to their water supply during or after nearby gas well drilling is shown in Figure 10. Attempts were made to individually evaluate each of these cases by comparing pre- and post-drilling water test results. Some perceived changes, such as odors, dissolved gases, foam, reduced flow or increased temperature, could not be evaluated because relevant test parameters were not always measured in post-drilling samples. Several complaints related to increased methane gas in Phase 2 water wells were already part of ongoing DEP investigations and could not be evaluated because methane was not measured in Phase 2 water wells.

The most common perceived changes by water well owners and reasons they contacted DEP were related to increased sediment and metals (Figure 10). Increased sediment or metals may originate from site disturbances and/or oxidation of the aquifer during the initial drilling stages. Perceived changes in metals concentrations were often described as increased orange, brown or black staining. In most cases where sediment or metals were perceived to increase due to drilling, there were no significant increases in sediment or metals concentrations between pre- and post-drilling samples.

Results of the water quality analyses did not confirm the few perceived water quality changes noted by Phase 1 water well owners, but there were three Phase 2 water wells where perceived changes did correlate to water quality results. These three cases each involved changes in sediment/metals. Each water well had pre-drilling manganese concentrations near or below the drinking water standard (0.05 mg/L) that increased far above the drinking water standard after drilling occurred (shown as circled points in Figure 11). These same water supplies had increased iron concentrations after drilling (Appendix I) and one also experienced a large increase in total suspended sediment (Appendix I). Manganese and iron concentrations above the drinking water standard would typically result in obvious black, brown and/or orange staining in the water supply.

It should be noted that changes in water well quality, whether naturally occurring or related to nearby land uses, are also related to seasonal, climatic or other variables. Testing of Phase 2 water wells was limited to two distinct points in time (pre- and post-drilling), which limits the ability to document such changes. More specific information was available from the 48 Phase 1 sites where water supply owners were provided with total dissolved solids meters to make daily measures of aspects of their water quality. Three water supply owners reported increases in excess of 50 mg/L in total dissolved solids during subsequent daily measurements. One TDS increase was

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determined to be related to a faulty meter. The other two cases also involved perceived changes in water quality. The researchers collected additional water samples at these two locations but there were no obvious changes in water chemistry to explain the changes observed by the water supply owner. One water supply owner pursued further action through a complaint to DEP.

Conclusions

While this study included a large number of water wells located across a large portion of the Marcellus region of the state, the results should be interpreted with caution. The investigators looked to combine a smaller but more controlled study (Phase 1) with a less robust investigation of a larger set of water wells. Both phases of the study relied on two point measures (pre- and post-drilling) and should not be used to infer potential impacts on water supplies at shorter or longer time scales. The researchers suggest that additional shorter- and longer-term monitoring is necessary to more precisely determine impacts at different time periods. Where comparable, results from both phases of the study produced similar results that can be used to infer some important conclusions and policy recommendations.

While only 233 private water wells were surveyed in this study, their water quality characteristics and pre-drilling impairment rates were very similar to previous results from a study of more than 700 private water wells in Pennsylvania (Swistock et al., 2009), indicating that the study wells are likely representative of the pre-drilling water quality conditions that occur in the large Marcellus region. Most of the private water wells in this study lacked recommended construction standards, presumably reflective of the lack of statewide water

Figure 10. Number of water well owners perceiving various water quality changes to their water well quality as a result of gas drilling activity.

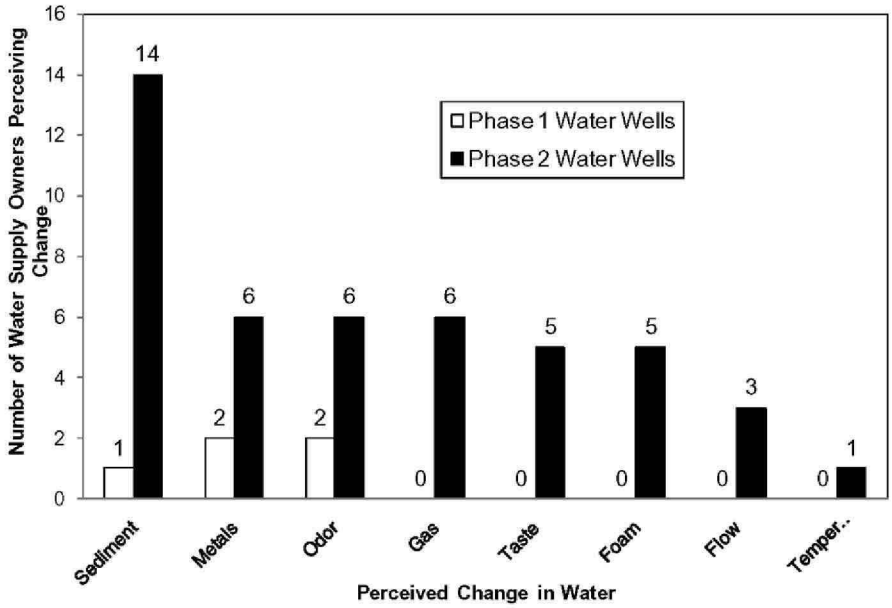
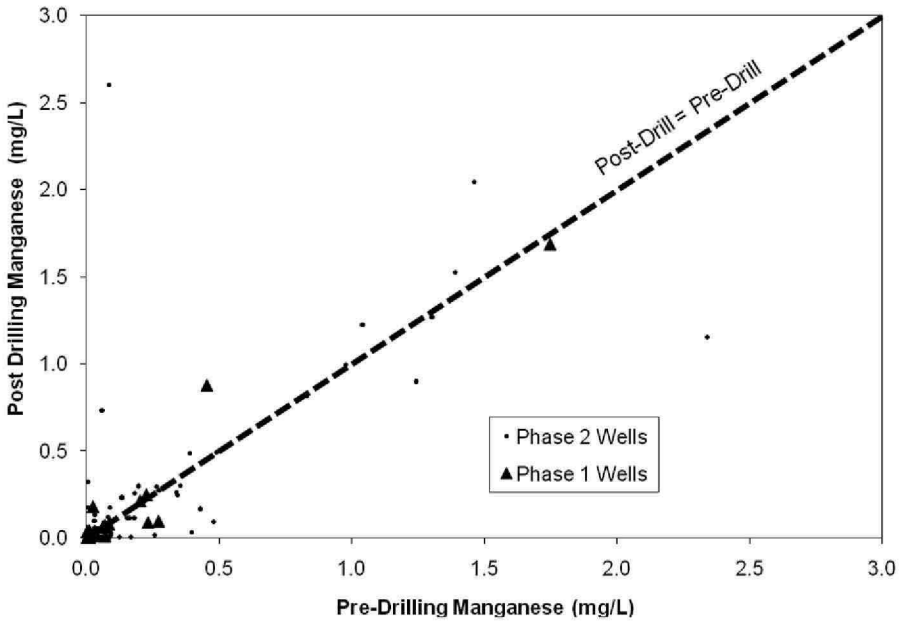


Figure 11. Comparison of pre-drilling manganese versus post-drilling manganese concentrations in water wells sampled in both phases of this study. Points above the diagonal dashed line represent water wells where the manganese level was higher in the post-drilling sample in comparison to the pre-drilling sample. Points below the diagonal dashed line indicate higher concentrations in the pre-drilling water sample. Circled points indicate water wells with owners that complained of obvious changes in water quality after gas drilling. Much of the scatter above and below the dashed line at low concentrations could be due to differing detection limits reported by water testing labs.



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well construction regulations, which likely contribute to impairments of certain water quality standards.

The current "presumed responsibility" stipulation in the Oil and Gas Act has resulted in extensive industry-sponsored analyses of pre-drilling water quality of most private water well supplies within 1,000 feet of Marcellus drilling operations. The rapid drop-off in pre-drilling analyses of water quality beyond this distance is driven by both the lack of presumed responsibility from the industry and also the cost of testing for water supply owners. While water supply owners often conducted much less extensive water testing, their frequent selection of proper chain-of-custody can be considered a public education success. But despite this plethora of water testing, many water supply owners had difficulty identifying pre-existing water quality problems in their water supply. Proper interpretation of water test reports appears to be an important factor impeding proper understanding of existing water quality problems. This fact was evident at several public workshops presented by the researchers during this project. Meetings that were marketed to explain pre-drilling water tests were well attended by water supply owners seeking unbiased information about the meaning of their water tests.

While most pre-drilling water test results were comparable to past studies, results for dissolved methane concentrations provided new information that documented its occurrence in about 20 percent of water wells. While pre-drilling methane levels were generally far below any advisory levels, there were sporadic pre-drilling occurrences of worrisome methane levels in some water wells in both phases of this study. Without a clear federal or state drinking water standard or sampling protocols, water supply owners are receiving a wide variety of confusing messages on methane in water.

Separate statistical analyses of the difference between pre-drilling and post-drilling water quality concentrations for both phases of this project did not suggest major influences of gas well drilling on the water quality of nearby water wells, as evidenced by a lack of statistically-significant increases in pollutants that are most prominent in drilling waste fluids, such as total dissolved solids, chloride, sodium, sulfate, barium, and strontium. The researchers obtained data on methane concentrations from 48 private water wells from Phase 1 where they could compare pre- to post-drilling methane levels. Among these samples, there were no statistically significant increases in methane levels after drilling, and no statistically significant correlations to distance from drilling. It also should be noted that the Marcellus gas wells near the Phase 1 water wells were generally drilled and fracked during late 2010 and early 2011 when amendments to Chapter 78 of the Oil and Gas Act were being implemented to, among other things, increase casing and cementing requirements for Marcellus gas wells to prevent methane migration issues. Several Phase 2 participants in this study were part of DEP investigations into methane migration that could not be evaluated in this study (methane was not included in Phase 2 post-drilling testing). Although the research did not find increased methane levels in water wells after drilling, past incidences and ongoing investigations clearly demonstrate the need for a more intensive study focused on the occurrence and sources of methane in water wells.

Although the results show a lack of widespread impacts from brines, fracking fluids or methane migration, increases in bromide levels at numerous Phase 1 sites in response to drilling and/or fracking may suggest more subtle impacts to groundwater that need more research. Bromide increases appeared to be mostly related to the drilling process although there was one case where bromide increases occurred in conjunction with other water quality parameters that are common in gas drilling waste fluids shown in Table 1. Bromide changes alone are not a direct health issue in unchlorinated groundwater supplies but bromide may hold promise as a more sensitive indicator of groundwater impacts since it is typically near or below detectable concentrations in undisturbed groundwater.

Sediment and/or metals (iron and manganese) increases due to aquifer disturbance during drilling can also show impacts to water wells from gas drilling. Overall, less than 1 percent of the water wells in this study showed quantitative evidence of sediment and/or metals increases that were noticeable to the water supply owner and confirmed by water testing results. Occasional changes to groundwater can be expected with any land disturbance or drilling activity, and are often short-lived, but they are still disruptive to water supply owners.

Water well owners indicated that gas drilling companies often complied with existing state regulations. Regulations requiring certified mail notification of water supply owners, chain-of-custody water sampling protocols, and DEP investigation of water supply complaints were generally followed although there were a few exceptions. However, voluntary lease stipulations intended to protect water well supplies were not frequently used by water supply owners in their gas drilling leases.

Policy Considerations

Results from this research suggest that updated regulations along with focused educational programs are needed to ensure proper protection and management of private water wells, which are an important source of drinking water for rural homeowners within the region of the state underlain by Marcellus Shale. This dual approach would seek to increase awareness among water supply owners about voluntary measures while providing reasonable regulatory protections. Specific policy recommendations follow.

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Water Testing

The necessity for costly testing of large numbers of water parameters to document pre-drilling water quality is limiting both the thoroughness and availability of water information for some private water supply owners. The current stipulation in the Oil and Gas Act that places presumed responsibility for water quality on gas drilling companies within 1,000 feet of their drilling sites resulted in relatively thorough industry-sponsored testing of pre-drilling water quality in 91 percent of the water wells within this distance. Water quality testing beyond 1,000 feet occurred much less frequently, owing to the costs and complexity of the analyses to be incurred by private well owners and the lack of presumed responsibility for gas drilling companies.

Results showed post-drilling increases in bromide concentrations and sporadic post-drilling increases in sediments and metals. These increases were generally detected in water wells within 3,000 feet of a nearby Marcellus gas well, but such results may not have been detected if looking at records for wells within only 1,000 feet.

The researchers assert that 3,000 feet is a more reasonable distance than the 1,000 feet that is currently required for both presumed responsibility and certified mail notification related to Marcellus gas well drilling. In the absence of an increase in the regulatory presumed-responsibility distance, the researchers suggest additional educational and financial resources to help facilitate additional voluntary testing among water supply owners.

Also, requiring a standardized list of minimum required testing parameters to be conducted across all pre-drilling surveys would eliminate many questions and confusion among both water well owners and water professionals and would better facilitate analyses of changes in elements of water quality. Results from this study suggest that this list should include bromide among other common parameters.

Education

The lack of awareness of pre-drilling water quality problems suggests that water supply owners would benefit from unbiased and consistent educational programs that explain and answer questions related to complex water test reports. This may best be accomplished through a standardized reporting form and supporting documents from an unbiased source. Penn State Extension's online Drinking Water Interpretation Tool (http://www.psiee.psu.edu/water/dwit.asp) is an example of a template that could be used for education on water test reports.

Regulation of Fracking

Results of the water quality parameters measured in this study do not indicate any obvious influence from fracking in gas wells on nearby private water well quality. Data from a limited number of wells also did not suggest a negative influence of fracking on dissolved methane in water wells. As a result, no clear policy recommendations can be made regarding alteration to current practices related to fracking. Impacts that did occur appeared to be related to disturbance or drilling activity rather than fracking.

However, it is important to note that this study largely focused on potential changes within a relatively short time period (usually less than six months) after fracking occurred, given the timeline of the project's funding. More detailed, longer-term studies are needed to provide a more thorough examination of potential problems related to fracking, and to investigate changes that might occur over longer time periods.

Drilling Locations

The Oil and Gas Act currently requires gas wells to be located at least 200 feet from water supplies. The shortest distance between a Marcellus gas well and water well in this study was 284 feet, suggesting compliance with the required setback distance. There were no statistically significant correlations between observed water quality changes and the distance between water wells and adjacent gas wells to support increasing the setback distance. All bromide increases in water wells occurred within 1,700 feet of a Marcellus gas well but there was no linear correlation with distance. While many rational arguments can be made to increase the required setback (for example, the scale of disturbance, materials used on the drilling pad, and location of pads within hydrologically sensitive areas of the landscape), the results from this project do not argue for an increased minimum setback distance.

Compliance with Current Regulations and Policies

Compliance with existing regulations and follow-up by DEP for water supply complaints were generally adequate with a few exceptions that occurred early in Marcellus gas drilling development. The researchers have recommended increased distances for certified mail notification and pre-drill survey water testing. A system of accrediting individuals who collect water samples would allow for easier documentation of compliance with chain-of-custody water testing requirements in the Oil and Gas Act.

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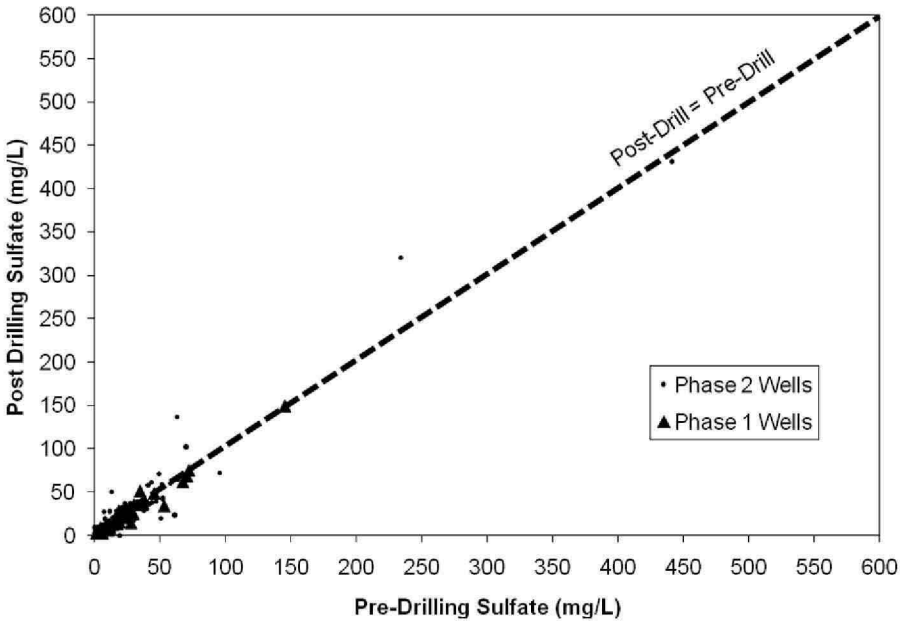
Appendix I

Additional Pre-Drilling Versus Post-Drilling Water Chemistry

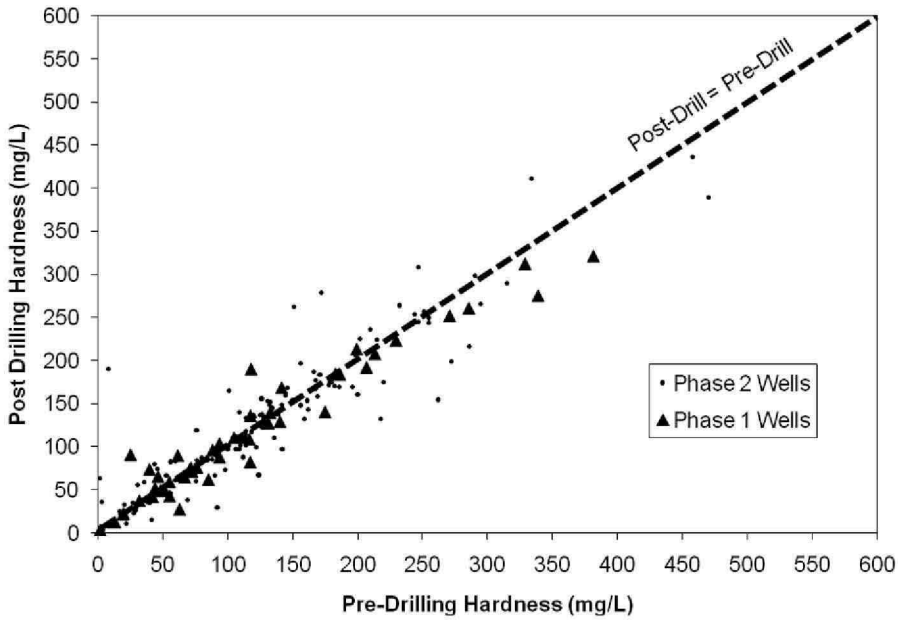
Sulfate

Comparison of pre-drilling sulfate versus post-drilling sulfate concentrations in water wells sampled in both phases of this study. Points above the diagonal dashed line represent water wells where the sulfate level was higher in the post-drilling sample in comparison to the pre-drilling sample. Points below the diagonal dashed line indicate higher concentrations in the pre-drilling water sample.



Hardness

Comparison of pre-drilling hardness versus post-drilling hardness concentrations in water wells sampled in both phases of this study. Points above the diagonal dashed line represent water wells where the hardness level was higher in the post-drilling sample in comparison to the pre-drilling sample. Points below the diagonal dashed line indicate higher concentrations in the pre-drilling water sample.



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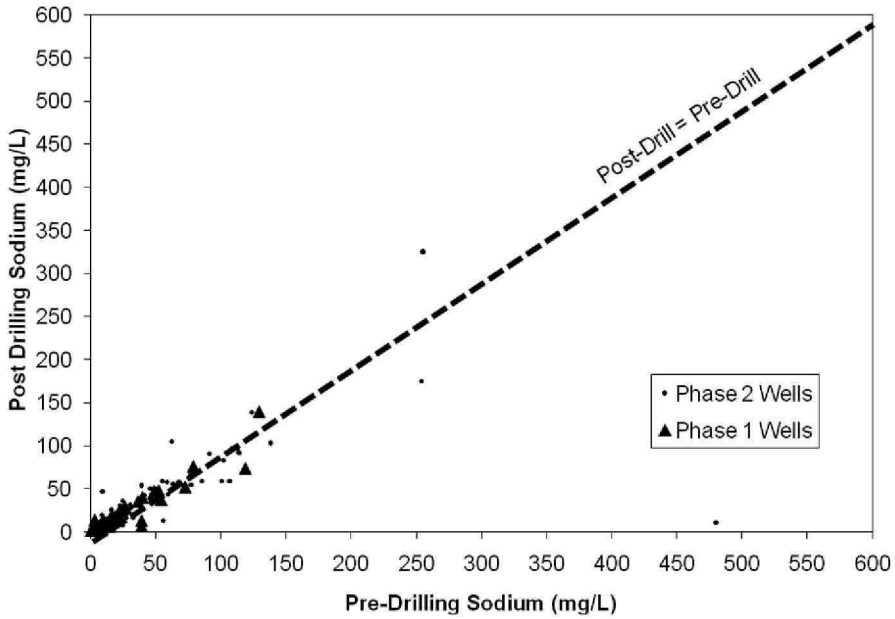
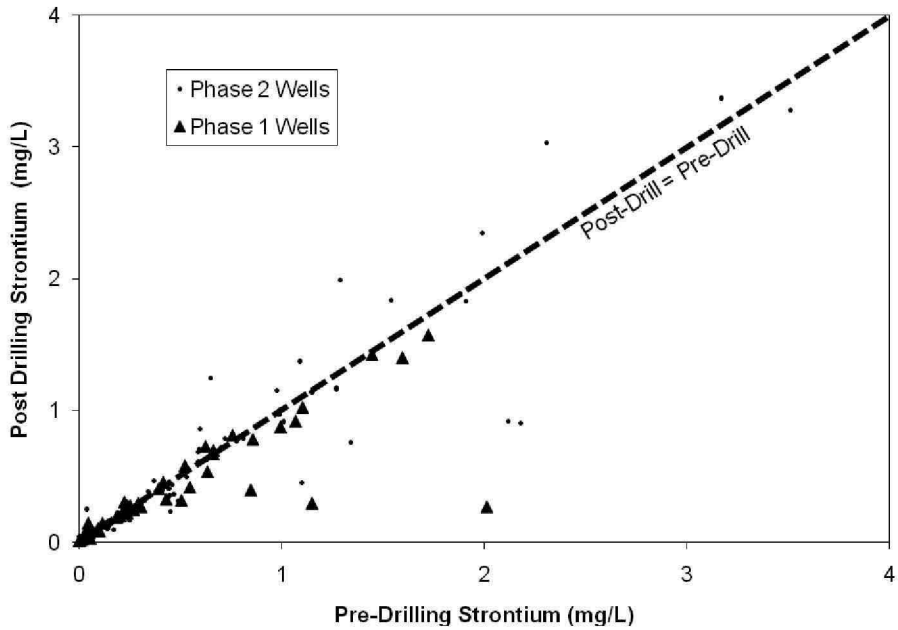
Sodium

Comparison of pre-drilling sodium versus post-drilling sodium concentrations in water wells sampled in both phases of this study. Points above the diagonal dashed line represent water wells where the sodium level was higher in the post-drilling sample in comparison to the pre-drilling sample. Points below the diagonal dashed line indicate higher concentrations in the pre-drilling water sample.



Strontium

Comparison of pre-drilling strontium versus post-drilling strontium concentrations in water wells sampled in both phases of this study. Points above the diagonal dashed line represent water wells where the strontium level was higher in the post-drilling sample in comparison to the pre-drilling sample. Points below the diagonal dashed line indicate higher concentrations in the pre-drilling water sample.



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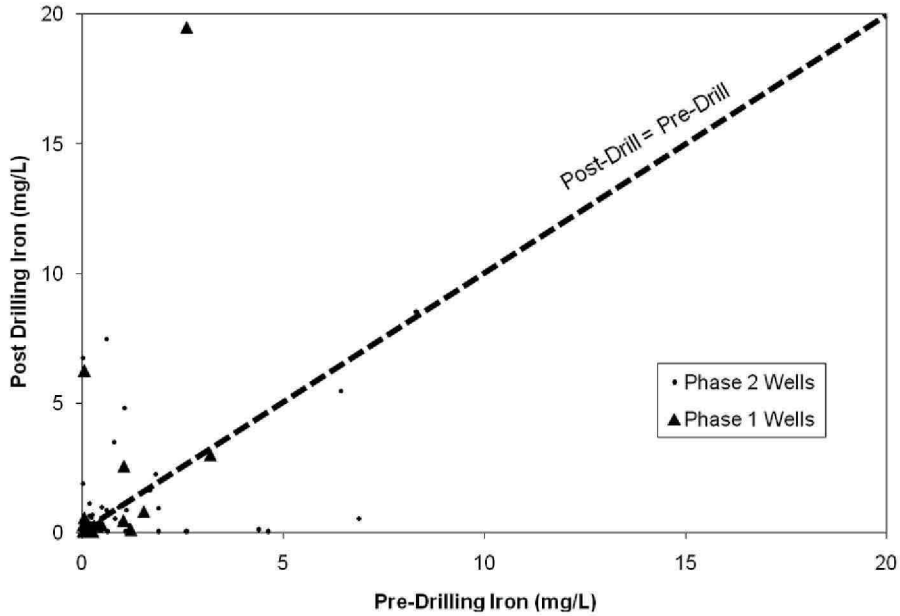
Appendix 1 (continued)

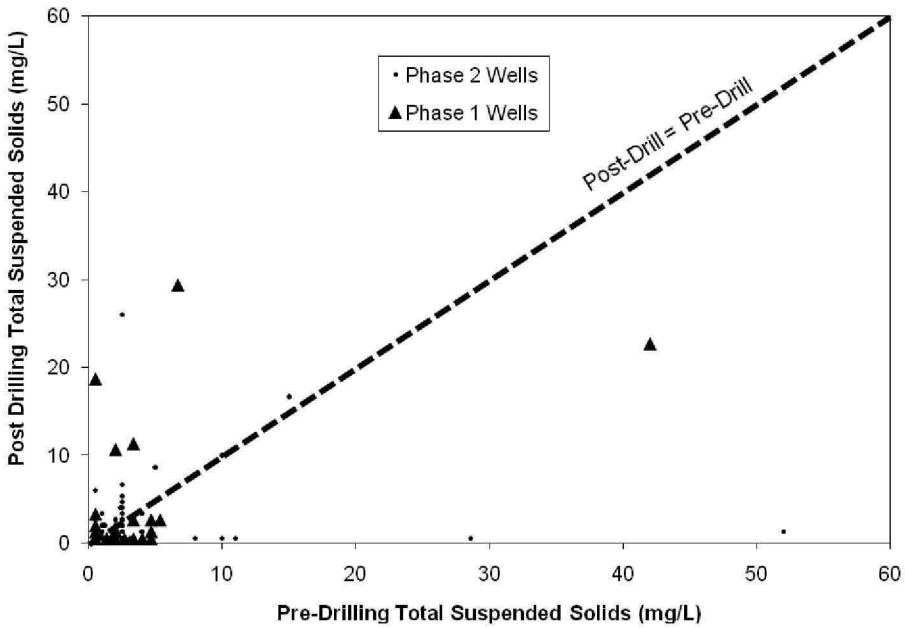
Iron

Comparison of pre-drilling iron versus post-drilling iron concentrations in water wells sampled in both phases of this study. Points above the diagonal dashed line represent water wells where the iron level was higher in the post-drilling sample in comparison to the pre-drilling sample. Points below the diagonal dashed line indicate higher concentrations in the pre-drilling water sample.



Total Suspended Sediment

Comparison of pre-drilling suspended sediment versus post-drilling suspended sediment concentrations in water wells sampled in both phases of this study. Points above the diagonal dashed line represent water wells where the sediment level was higher in the post-drilling sample in comparison to the pre-drilling sample. Points below the diagonal dashed line indicate higher concentrations in the pre-drilling water sample.



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