

Prepared in cooperation with Miami Conservancy District

The Effectiveness of Water-Treatment Systems for Arsenic Used in 11 Homes in Southwestern and Central Ohio, 2013



Scientific Investigations Report 2015–5156

Cover. Photographs of domestic wells and arsenic treatment systems.

Photograph credits: Mary Ann Thomas, USGS (top left); Donna Runkle, USGS (center); and Mike Ekberg, Miami Conservancy District (top right, bottom right, bottom left).

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
ounce, fluid (fl. oz)	0.02957	liter (L)
gallon (gal)	3.785	liter (L)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as
 $^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$ at 25 °C).

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Supplemental Information

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter ($\mu\text{g}/\text{L}$).

The Effectiveness of Water-Treatment Systems for Arsenic Used in 11 Homes in Southwestern and Central Ohio, 2013

By Mary Ann Thomas and Mike Ekberg

Abstract

In 2013, the U.S. Geological Survey and the Miami Conservancy District investigated the effectiveness of methods used to remove arsenic from drinking water at 11 homes in southwestern and central Ohio. The untreated (raw) ground-water had arsenic concentrations of 7.7–382 micrograms per liter ($\mu\text{g/L}$), and the median concentration was 30 $\mu\text{g/L}$. The pH was neutral to slightly alkaline, and redox conditions were strongly reducing, as indicated by high concentrations of iron. The predominant arsenic species was arsenite (As^{3+}), which is difficult to treat because it exists in water as an uncharged compound (H_3AsO_3).

The water-treatment systems included (1) seven single-tap reverse-osmosis systems, (2) two whole-house oxidation/filtration systems, and (3) two systems that included whole-house anion exchange and single-tap reverse osmosis. All but one system included pretreatment by a water softener, and two systems included preoxidation to convert arsenite (As^{3+}) to arsenate (As^{5+}) before treatment by anion exchange.

None of the treatment systems removed all of the arsenic from the drinking water. About one-half of the systems decreased the arsenic concentration to less than the maximum contamination level of 10 $\mu\text{g/L}$. The effectiveness of the systems varied widely; the percentage of arsenic removed ranged from 2 to 90 percent, and the median was 65 percent.

At some sites, the low effectiveness of arsenic removal may have been related to system maintenance and/or operation issues. At two sites, homeowners acknowledged that the treatment systems had not been maintained for several years. At two other sites, the treatment systems were being maintained, but the water-quality data indicated that one of the components was not working, unbeknownst to the homeowner. EPA research at a small number of sites in Ohio indicated that operation and maintenance of some arsenic-treatment systems was not always simple.

Another factor that affected system effectiveness was the quality of the raw water. In general, the treatment systems were less effective at treating higher concentrations of arsenic. For five sites with raw-water arsenic concentrations of 10–30 $\mu\text{g/L}$, the systems removed 65–81 percent of

the arsenic, and the final concentrations were less than the maximum contamination level. For three sites with higher raw-water arsenic concentrations (50–75 $\mu\text{g/L}$), the systems removed 22–34 percent of the arsenic; and the final concentrations were 4–5 times more than the maximum contamination level. Other characteristics of the raw water may have affected the performance of treatment systems; in general, raw water with the higher arsenic concentrations also had higher pH, higher concentrations of organic carbon and ammonia, and more reducing (methanogenic) redox conditions.

For sites with raw-water arsenic concentrations of 10–30 $\mu\text{g/L}$, two types of systems (reverse osmosis and oxidation/filtration) removed similar amounts of arsenic, but the quality of the treated water differed in other respects. Reverse osmosis caused substantial decreases in pH, alkalinity, and concentrations of most ions. On the other hand, oxidation/filtration using manganese-based media caused a large increase of manganese concentrations, from less than 50 $\mu\text{g/L}$ in raw water to more than 700 $\mu\text{g/L}$ in outflow from the oxidation/filtration units.

It is not known if the results of this study are widely applicable; the number of systems sampled was relatively small, and each system was sampled only once. Further study may be warranted to investigate whether available methods of arsenic removal are effective/practical for residential use in areas like Ohio, where groundwater with elevated arsenic concentrations is strongly reducing, and the predominant arsenic species is arsenite (As^{3+}).

Introduction

Most instances of widespread arsenic contamination of groundwater are the result of natural sources of arsenic (Smedley and Kinniburgh, 2002). Arsenic is often a minor component of the rocks or sediments of the aquifer matrix, and it can be released to the groundwater under certain geochemical conditions. Long-term exposure to arsenic through drinking water is associated with multiple serious health problems. Arsenic is a known human carcinogen linked to cancers of the bladder, lungs, skin, kidney, nasal passages, liver, and

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prostate. In addition, exposure to arsenic has been determined to interfere with the immune system; affect cardiovascular, pulmonary, neurological, and hormonal processes; and may be an important contributor to the development of type 2 diabetes (U.S. Environmental Protection Agency, 2001; International Agency for Research on Cancer, 2004; World Health Organization, 2010). The U.S. Environmental Protection Agency (EPA) has determined that the concentration of arsenic with no known or expected health risk is 0 microgram per liter ($\mu\text{g/L}$) (referred to as the maximum contaminant level goal [MCLG]). The highest level of arsenic allowed in drinking water from public-water systems is 10 $\mu\text{g/L}$ (referred to as the maximum contaminant level [MCL]). The MCL is higher than the MCLG because cost of treatment is taken into consideration (U.S. Environmental Protection Agency, 2009). In this report, arsenic concentrations greater than 10 $\mu\text{g/L}$ are referred to as “elevated.”

Arsenic is a relatively common contaminant in Ohio groundwater; 17 percent of public-water systems (about one in six) had arsenic concentrations greater than the MCL in raw, untreated water (Ohio Environmental Protection Agency, 2010b). The Ohio EPA requires that public-water systems monitor for arsenic, and the average annual concentration in finished water cannot exceed 10 $\mu\text{g/L}$. Domestic wells of Ohio are not routinely tested for arsenic. (MCLs are not enforceable for domestic wells but are often used as health guidelines.) About 1.8 million Ohio residents rely on domestic wells (Maupin and others, 2014), and most do not know the arsenic concentration of their water. As more people become aware of the potential health problems associated with arsenic in drinking water, they may seek guidance about water treatment methods.

Removing arsenic from groundwater is complex. One reason is that inorganic arsenic can exist in groundwater as two different species; arsenate (As^{5+}) is generally the predominant species in oxic groundwater, and arsenite (As^{3+}) is generally the predominant species in reducing groundwater. Arsenate (As^{5+}) is easier to remove from water because it typically exists as a negatively charged compound (HAsO_4^{2-} or HAsO_4^-). On the other hand, As^{3+} exists as an uncharged compound (H_3AsO_3), and therefore is harder to remove by treatment processes. (In addition, As^{3+} is generally considered to be more toxic to humans than As^{5+} .)

In Ohio and the other parts of the Midwest, arsenic in groundwater is predominantly As^{3+} , whereas As^{5+} is the predominant species in other regions of the United States (Sorg and others, 2014). There are also regional differences in other

water-quality constituents that affect arsenic mobility (and effectiveness of arsenic removal) including redox conditions, pH, and concentrations of oxyanions.

The effectiveness of any water treatment method depends on the chemical characteristics of the water being treated; therefore, treatment methods that are effective in other parts of the Country may be less effective in Ohio. Much of the available research about treating water for arsenic relates to large public-water systems in the western U.S. or to primitive wells in remote villages of southeastern Asia (for example, Ahuja [2008] and references therein). Very few studies have been done to test the effectiveness and applicability of methods for treating arsenic in groundwater characteristic of Ohio or other parts of the Midwest. In 2013, the U.S. Geological Survey (USGS), in cooperation with the Miami Conservancy District (MCD), did an investigation of arsenic-treatment systems used in homes of southwestern and central Ohio. Because of the small number of systems sampled, results of this study cannot be used to determine whether one type of system is better than another; however, results of the study provide an initial snapshot of residential arsenic treatment that can be used to guide the design of future studies.

Purpose and Scope

The purpose of this report is to document the effectiveness of methods used to treat arsenic in water from 11 domestic wells in southwestern and central Ohio. The goals are to (1) describe the chemical characteristics of the groundwater, (2) describe the types of water-treatment system in use, and (3) document differences between raw groundwater and treated water with emphasis on arsenic concentrations and speciation.

A total of 11 homes in Preble, Darke, Montgomery, Greene, Clark, and Licking Counties, Ohio, were selected for study. Unfiltered samples of raw and treated water were collected from each home once during 2013. Samples were analyzed at the USGS National Water Quality Laboratory (NWQL) for arsenic, arsenic species, major ions, trace elements, nutrients, and total organic carbon. Homeowners provided information about the type, age, and maintenance history of the treatment systems. Graphical methods and summary statistics were used to document (1) the chemical characteristics of the raw water, (2) the effect of the treatment systems on concentrations of total arsenic and arsenic species, and (3) factors related to the effectiveness of the treatment systems.

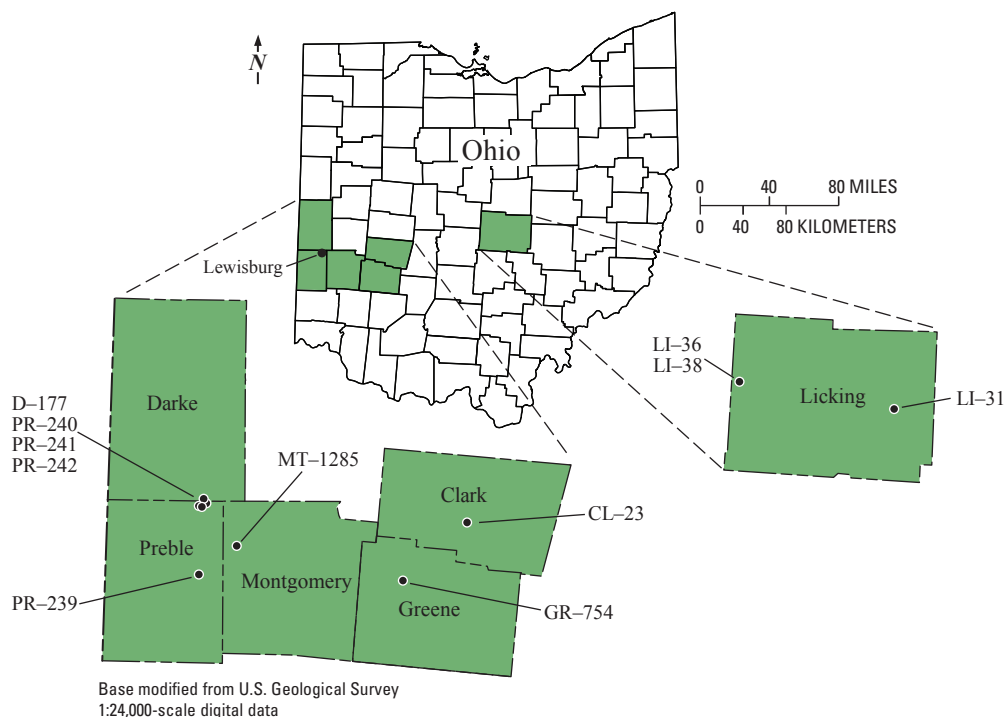


Figure 1. Location of 11 study sites in southwestern and central Ohio.

Description of Study Area

The wells sampled for this study are in Licking County (central Ohio), and five counties within the Great Miami River watershed (southwestern Ohio) (fig. 1). These are areas where arsenic in groundwater has been investigated or documented by Dumouchelle (1999), Ohio Department of Health (1999), Shindel and others (2000), Miami Conservancy District (2011), Thomas and others (2005, 2008), and Thomas (2016). The hydrogeology of the Great Miami River Basin has been summarized by Debrewer and others (2000) and the Miami Conservancy District (2013). The hydrogeology of Licking County has been described by Dove (1960), Angle (1995), and Siegrist and others (1997). The glacial and bedrock geology of both areas has been mapped by Ohio Department of Natural Resources as part of statewide and county coverages (Ohio Department of Natural Resources, n.d.).

The geology of southwestern and central Ohio consists of Paleozoic sedimentary bedrock overlain by Pleistocene glacial deposits. In southwestern Ohio, bedrock consists of carbonates and shales of Ordovician-Silurian age, and glacial deposits are predominantly from the Miami Lobe of the Wisconsin glacial advance. In Licking County, bedrock is predominantly interbedded shales and sandstones of Devonian-Pennsylvanian age, and glacial deposits are from the Scioto Lobe. Despite these differences, many aspects of the hydrogeology are similar. In both areas, deep valleys were cut into bedrock by

the preglacial Teays River system and subsequently filled with glacial deposits (and are referred to as “buried valleys”). In buried valleys, glacial deposits are 200 to more than 600 feet (ft) thick, and in uplands between buried valleys, glacial deposits are generally 0–200 ft thick. Layers or lenses of sand and gravel in the glacial deposits serve as aquifers. Over most of the area, the sand and gravel deposits are overlain by relatively fine-grained material (till or clay), and the aquifers are confined or semiconfined. In the vicinity of modern rivers, sand and gravel occurs at land surface, and the glacial aquifers are unconfined.

In southwestern and central Ohio, water wells tap bedrock and (or) the overlying glacial deposits. Elevated concentrations of arsenic have been detected in both types of aquifers but are generally higher in glacial aquifers. In southwestern Ohio, a survey of arsenic in 107 wells determined that 20 percent of domestic wells in the Great Miami River Basin had elevated arsenic (Miami Conservancy District, 2011). In Licking County, a study of 168 domestic wells determined that 12 percent had elevated arsenic concentrations (Thomas, 2016). In both areas, elevated concentrations of arsenic were detected in groundwater with similar chemical characteristics: iron concentrations were greater than about 800 $\mu\text{g/L}$, redox conditions were strongly reducing, and the pH was neutral to slightly alkaline. In both areas, the highest arsenic concentrations were detected in methanogenic water in confined buried-valley aquifers (Thomas and others, 2005, 2008).

Sidebar—Arsenic Treatment Terms Used in this Report

Brief explanations of the processes discussed in this report are provided below. The information is from U.S. Environmental Protection Agency (2003), Ohio Environmental Protection Agency (2010a), National Ground Water Association (2009), and Thomas Sorg, U.S. Environmental Protection Agency (written and verbal commun., 2013).

There are two general types of water-treatment systems:

- Point-of-entry (POE) systems treat all of the water that enters a home—usually 250 or more gallons per day. The POE systems are also referred to as “whole-house” systems.
- Point-of-use (POU) systems treat water from a single faucet. They are often installed on the kitchen sink and treat only the water used for drinking and cooking—usually a few gallons per day. The POU systems are also referred to as “single-tap” systems.

Four processes for removing arsenic from water are discussed in this report:

- Reverse-osmosis removes arsenic by forcing water past a semipermeable membrane that allows water molecules to pass but blocks most dissolved constituents. Treated water on the other side of the membrane flows to a small pressure storage tank until needed. The process is more effective for removing As^{5+} than As^{3+} . The rejected water is disposed of through a sewer or septic system. For every gallon of water that is treated, more than 3 gallons are disposed of. Reverse-osmosis systems remove most of the dissolved constituents in water, including bicarbonate, so the treated water will likely be more acidic than the raw water. Reverse osmosis is relatively and widely available as a single-tap system. In general, reverse-osmosis systems have been determined to remove 50–60 percent of As^{3+} and at least 90 percent of As^{5+} (Thomas Sorg, U.S. Environmental Protection Agency, 2015, written commun.).
- Anion exchange is a physical/chemical process in which anions are exchanged between water and a solid resin. The As^{5+} exists as an anion and can displace chloride from a chloride-based resin. The As^{3+} is not removed by anion resins, so pretreatment to convert As^{3+} to As^{5+} is required. The effectiveness of anion exchange is dependent on concentrations of sulfate and other anions that compete with As^{5+} for binding sites. The resin is regenerated by passing a salt solution through the resin tank, which replaces As^{5+} and other anions with chloride. The resulting

brine solution contains the arsenic and other anions. If regeneration of the media is not frequent enough, arsenic concentration of the treated water can exceed that of the raw water. Because anion exchange systems remove the bicarbonate anion, the treated water will likely be more acidic than the raw water. Anion exchange is usually available as a whole-house system.

- Oxidation/filtration using solid manganese (Mn)-based media causes iron and manganese to precipitate out of the water as oxides or oxyhydroxides. Arsenic has a high affinity for oxyhydroxides, so some of the arsenic precipitates along with the iron (or manganese), and the particles are filtered out of the water. The Mn-based media can be natural or artificial. The solid media is regenerated by a backwash process that can require high pressures. Oxidation/filtration systems are usually available as whole-house systems.
- Adsorption using Fe-based media works by passing water through a cartridge of iron (Fe)-based adsorptive media, and the arsenic sorbs to the surface of the media. The removal capacity for As^{3+} is substantially less than for As^{5+} , so pretreatment to convert As^{3+} to As^{5+} is often recommended. Other names for Fe-based adsorptive media include granular ferric oxide (GFO), and granular ferric hydroxide (GFH). In addition to Fe-based products, other available products include Fe-modified activated alumina, Fe-modified anion resins, and several titanium-based granular media. All media products have a limited capacity for arsenic removal. Once the capacity is reached, the media is thrown away and replaced with new media. Adsorption is usually available as whole-house or single-tap systems.

One or more forms of pretreatment is recommended or required before the arsenic-removal step:

- Water softeners are often used as a form of pretreatment to remove high concentrations of Fe or Mn, which can foul the membranes or media used for arsenic removal.
- Preoxidation refers to a process that converts As^{3+} to As^{5+} before treatment by other methods. Preoxidation is required before anion exchange if arsenic is present as As^{3+} . In addition, preoxidation is recommended for reverse osmosis, oxidation/filtration, and Fe-based adsorption. Oxygen is not effective at oxidizing As^{3+} . Methods used for preoxidation include chlorination, ozone, and oxidation using Mn-based media.

Previous Studies

In 2009–10, the Miami Conservancy District sampled 107 domestic wells in southwestern Ohio to document arsenic concentrations in groundwater of the Great Miami River watershed (Miami Conservancy District, 2011). As part of that study, pairs of raw and treated water samples were analyzed for nine wells with treatment systems consisting of water softeners and single-tap reverse-osmosis units. Four of the nine systems decreased the arsenic concentrations to less than 2 µg/L; however, for two of the nine systems, the arsenic concentrations of treated water were greater than the MCL of 10 µg/L. These systems were resampled after being serviced by a professional technician or the homeowner, and one of the systems still produced water that did not meet the MCL. The overall conclusions of the study were that (1) private well owners must be aware that all arsenic might not be removed by water-treatment systems, and (2) the water-treatment systems must be maintained.

Arsenic treatment methods have been evaluated for domestic wells in other states, but it is difficult to translate these results to Ohio, where the water quality and arsenic speciation may be different. Walker and others (2008) evaluated single-tap, reverse-osmosis systems in 59 households in rural Nevada. The conclusion was that two factors affected the results—the arsenic concentration in the raw water and the arsenic speciation. Reverse osmosis worked well in the 85 percent of wells in which As^{3+} was the predominant species; however, removal efficiency was reduced for the 15 percent of the wells that had As^{3+} as predominant species. Another conclusion was that specific conductance (SC) measurements, which are used by technicians to determine whether reverse-osmosis systems are operating, were not sufficient to determine effectiveness of arsenic removal. Investigations of the performance of arsenic treatment using Fe-based adsorptive media were done in New Jersey (Spayd, 2007, 2009) and North Carolina (Pratson and others, 2009). The treatment systems were judged to be effective at decreasing arsenic concentrations to less than the MCL.

U.S. Environmental Protection Agency Studies of Arsenic Removal Technology

After the MCL was lowered from 50 to 10 µg/L in 2001, the EPA instituted a research program to evaluate arsenic removal technologies for use in small public-water systems (U.S. Environmental Protection Agency, 2010). Arsenic removal technology demonstration studies and pilot-scale studies were completed at sites across the United States, four of which were in Ohio.

Small Public-Water Systems in Ohio

One of the EPA arsenic removal technology demonstration sites was a mobile home park in Clark County, Ohio

(McCall and others, 2007). The average arsenic concentration of the raw water was 21.5 µg/L, and the predominant species was As^{3+} . The arsenic treatment system included chlorination, oxidation/filtration using Mn-based media, and adsorption using Fe-based media. The treatment system decreased arsenic concentrations to less than the MCL. Skill was required to operate the system, and several revisions were necessary to maintain acceptable levels of free and total chlorine in the treated water (McCall and others, 2007).

Another arsenic removal technology demonstration site was a preschool in Licking County, Ohio (Chen and others, 2011). Average arsenic concentration in the raw water was 15.2 µg/L, and the predominant species was As^{3+} . The arsenic treatment system included a water softener, chlorination, and adsorption using Fe-based media. During almost 4 years of operation, the system reduced arsenic concentrations to an average of 1.3 µg/L; however, significantly elevated concentrations of disinfection byproducts (DBP) were detected in the treated water. The investigators hypothesized that the Fe-based adsorptive media could promote the formation of DBP if the influent water contained chlorine and total organic carbon (Chen and others, 2011).

A pilot-scale arsenic removal technology study was done at a high school in Licking County, Ohio (U.S. Environmental Protection Agency, 2011). The average arsenic concentration of the raw water was 69 µg/L, which was almost all As^{3+} . The arsenic treatment system included potassium permanganate oxidation, oxidation/filtration using Mn-based media, and chlorination. The system removed 93 percent of the arsenic during the first 6 months of operation; however, elevated Mn concentrations were detected in the treated water, and investigators concluded that it had likely leached from the Mn-based media used for oxidation/filtration. Multiple attempts were made to try to maintain low concentrations of Mn and arsenic in the treated water (U.S. Environmental Protection Agency, 2011).

In addition, raw water from the Licking County High School was used as part of a lab-based investigation of the effectiveness of four types of adsorptive media: granular ferric hydroxide (GFH), Fe oxide-based media, hybrid ion-exchange media, and modified activated alumina. Results of the study indicated that GFH outperformed the other media (Benn, 2006). A comparison of results between the lab-based and pilot-scale studies indicated that the life of the adsorptive media was lower in pilot-scale studies than in the lab-based studies (Westerhoff and others, 2008).

Domestic Wells in Ohio

In 1998, elevated concentrations of arsenic were detected in domestic wells in the vicinity of a waste site near Lewisburg, Ohio (fig. 1). (Further investigation indicated that the source of the arsenic was natural and not related to the waste site [Ohio Department of Health, 1999].) As part of remedial actions, EPA contractors installed arsenic treatment systems in 28 homes (Wang and others, n.d.). The systems included a

sediment filter, water softener, preoxidation using Mn-based media, anion exchange, and single-tap reverse osmosis. From 1998–2001, the systems were periodically monitored, and results indicated that arsenic concentrations were less than the MCL, which was 50 $\mu\text{g/L}$ at that time. In 2004, some of the sites were revisited as part of EPA-sponsored studies. The home with the highest arsenic concentration was included as one of the EPA arsenic removal technology demonstration sites (Wang and others, n.d.). The raw water had an average arsenic concentration of 453 $\mu\text{g/L}$, which was mostly As^{3+} . The treatment system was initially successful at decreasing the arsenic concentration to less than the MCL, but the results could not be sustained. The EPA and its contractors revised the treatment system three times between 2004 and 2011. The final system included aeration to remove methane, preoxidation by chlorination, carbon filtration, water softening, anion exchange, and a single-tap reverse osmosis. This site is included in the current study along with three others in the Lewisburg area that had arsenic treatment systems installed by the EPA in 1998.

Methods

Site Selection

The criteria for selecting study sites were that (1) a domestic well produces water with an arsenic concentration greater than the MCL of 10 $\mu\text{g/L}$, and (2) a water-treatment system for reducing arsenic concentrations is in use. To identify potential sites, letters were sent to homeowners who had participated in earlier arsenic investigations by the USGS and MCD (Thomas and others, 2005; Miami Conservancy District, 2011). In addition, letters were sent to personnel at the Ohio Department of Health and local health departments in six counties to request help in identifying potential participants. A total of 31 letters were sent out, and, of those, 4 positive responses were received. To increase the number of study participants, letters were sent to homeowners in Preble and Darke Counties, the area where the EPA and its contractors had installed arsenic treatment systems in homes as part of remedial actions near a waste site (Ohio Department of Health, 1999). To further increase the number of study participants, the study area was expanded to include Licking County in central Ohio. During 2012, 168 domestic wells in Licking County were tested for arsenic (Thomas, 2016), and, of those, 3 were identified as meeting the selection criteria.

The final dataset includes three homes in Licking County and eight homes in southwestern Ohio. For 6 of the 11 sites, the water-treatment system was installed specifically to treat arsenic. For the other five sites, the system was not installed for the purpose of treating arsenic, but is one of the types of systems recommended for arsenic treatment.

Data Collection and Analysis

Water-treatment systems in 11 homes were sampled once in 2013. Six homes were sampled during a week in April, and the other five homes were sampled during a week in June. The methods used for collection and analysis of water-quality samples are summarized in table 1. A minimum of two water samples were collected at each home: a raw sample (untreated groundwater from the well), and a final sample (fully treated water from the kitchen faucet). In addition, at most homes it was possible to collect at least one “intermediate” sample along the treatment train (for example, after the water softener and before the reverse-osmosis system). The total number of environmental samples collected was 36.

None of the samples was filtered at the time of collection; therefore, all laboratory results represent total concentrations. The final samples were not filtered because the goal was to document the quality of the water being consumed by homeowners. The raw and intermediate samples also were not filtered because the goal was to identify water-quality changes attributed only to the effects of the home-treatment systems.

Samples of raw water were collected following documented procedures for well purging, field measurements, sample withdrawal, collection and preservation, and quality assurance (U.S. Geological Survey, 2012). Measurements of specific conductance, pH, temperature, and acid-neutralizing capacity (ANC) were made in the field at the time of sample collection. Samples were analyzed for major ions, trace elements, nutrients, total organic carbon, and arsenic speciation at the USGS NWQL in Denver, Colorado.

Final and intermediate samples were collected using similar methods as raw samples, except that bottles were filled directly from a faucet inside the home. Before filling sample bottles, the plumbing lines were flushed for several minutes to remove standing water. Field measurements of specific conductance, pH, temperature, and ANC were made using the subsample method (readings were taken from a multiparameter sonde immersed in a measurement vessel).

While water samples were being collected by a two-person team, a third person briefly interviewed homeowners about their water-treatment systems. The questions were primarily related to when and how each component of the treatment system was purchased and installed and whether the system was being actively maintained by either the homeowner or a professional. Information was not collected about type and frequency of system maintenance or the amount of water used in each home. Information about well construction and aquifer characteristics were not available for every well. Only 4 of the 11 wells had well logs on file at the Ohio Department of Natural Resources. Homeowners reported approximate depths of three of the wells that did not have well logs.

Table 1. Methods used for collection and analysis of water samples from 11 domestic wells in southwestern and central Ohio, 2013.

[NWQL, National Water Quality Laboratory; WG, groundwater; HHXX, time designation used to identify position of sample in treatment train; USGS, U.S. Geological Survey; SC, specific conductance; ANC, acid-neutralizing capacity; DO, dissolved oxygen; WT, treated water]

Sample type	Sample type identifier	Sample collection methods	Field measurements	Constituents analyzed at NWQL
Raw (groundwater from well-head)	Medium=WG Time= HH00	Standard USGS methods for groundwater (U.S. Geological Survey, variously dated)	pH, SC, DO, temperature, turbidity, and ANC	Trace elements, arsenic speciation, major ions, nutrients, and total organic carbon (Fishman, 1993; Brenton and Arnette, 1993; Garbarino and others, 2012).
Intermediate (partially treated water collected along treatment train)	Medium=WT Time= HH51, HH52, HH53, HH54	Collected samples from taps inside home. Field measurements were made using subsample method (U.S. Geological Survey, variously dated)	pH and SC	
Final (fully treated water from kitchen faucet)	Medium=WT Time= HH59		pH, SC, and ANC	

Quality Assurance

Quality-control (QC) samples were collected following USGS procedures (U.S. Geological Survey, var. dated) and analyzed at the NWQL. Before the start of each week of sampling, an equipment blank was collected to assess bias related to the sampling equipment or decontamination procedures. During each week of sampling, two additional QC samples were collected: a replicate (to assess variability because of field or laboratory practices), and a field blank (to assess bias because of field or laboratory practices or conditions). For each equipment and field blank, a source-solution blank (a sample of the contaminant-free water used for the equipment and field blanks) was also analyzed. Over the 2-week sampling period, a total of two equipment blanks, two replicates, two field blanks, and four source-solution blanks were collected.

Equipment blanks and field blanks were analyzed for trace elements and major ions, and one of the field blanks was also analyzed for total organic carbon. The data were not tabulated herein because all constituents were not detected or detected at a concentration that was less than the laboratory reporting level. The only exception was boron, which was detected in one of the equipment blanks at a concentration

greater than the laboratory reporting level; however, a similar concentration of boron was also detected in the associated source-solution blank, so the detection is not considered to be a problem.

Replicate samples were analyzed for arsenic speciation, and one of the replicates was also analyzed for nutrients. Arsenic speciation results for one sample showed a relatively high amount of variability: compared to the environmental sample, the replicate sample was 19 percent lower in terms of As^{3+} and 20 percent higher in terms of As^{5+} . In addition, arsenic speciation results for environmental samples were a cause for concern because the sum of As^{3+} and As^{5+} concentrations did not equal the total arsenic concentration for most sites. It is not known whether this variability was the result of field or lab activities; however, these issues were considered to be acceptable for this study because the speciation data are used in a semiquantitative way to identify the predominant species of arsenic in each water sample.

USGS personnel collected a total of 36 samples of raw and treated water from 11 homes. Ten additional samples were collected for quality assurance. Photograph by Ralph Haefner, USGS.



Quality of Raw Water

The effectiveness of a water-treatment method depends on the chemistry of the water being treated. This section of the report presents water-quality characteristics of raw water with emphasis on arsenic concentrations, arsenic speciation, and concentrations of constituents that affect the performance of arsenic-treatment methods. Raw and treated water-quality data are presented in table 2 (see page 26, or the Excel file can be accessed at <http://dx.doi.org/10.3133/sir20155156>).

Total Arsenic and Arsenic Species

Samples of untreated (raw) groundwater were collected from the wellheads at 11 homes. Total arsenic concentrations ranged from 7.7 to 382 $\mu\text{g/L}$, and the median concentration was about 30 $\mu\text{g/L}$. A total of 10 samples had arsenic concentrations greater than the MCL of 10 $\mu\text{g/L}$ (fig. 2).

Raw water samples were analyzed for concentrations of four arsenic species: two inorganic species (As^{5+} and As^{3+}) and two organic species (dimethylarsinate and monomethylarsonate). The organic species were not detected at concentrations above the lab reporting limits (0.6 $\mu\text{g/L}$ and 3.2 $\mu\text{g/L}$, respectively).

Arsenite (As^{3+}) was the predominant species in 10 of 11 raw water samples (fig. 2). For these 10 samples, the fraction of As^{3+} was 70–92 percent. These results are consistent with the limited amount of arsenic speciation data available for Ohio groundwater (Sorg and others, 2014; Thomas and others, 2008). As^{3+} exists as an uncharged compound (H_3AsO_3), and therefore is harder to remove by treatment processes. On the other hand, arsenate (As^{5+}) is easier to remove from water because it typically exists as negatively-charged compound (HAsO_4^{2-} or HAsO_4^-).

One sample (D-177) was unusual in that the arsenic was predominantly (99 percent) As^{5+} . The Fe concentration of the water was unusually high (15,800 $\mu\text{g/L}$). In addition, concentrations of orthophosphate, zinc, nickel, lead, vanadium, aluminum, cadmium, and cobalt that were much higher than the other 10 samples. It is not known why this sample was so different from the others. It is possible that groundwater at this site is unique with respect to the arsenic source and/or mechanism of mobilization. (No well log was found for this site, so details about the aquifer characteristics and well

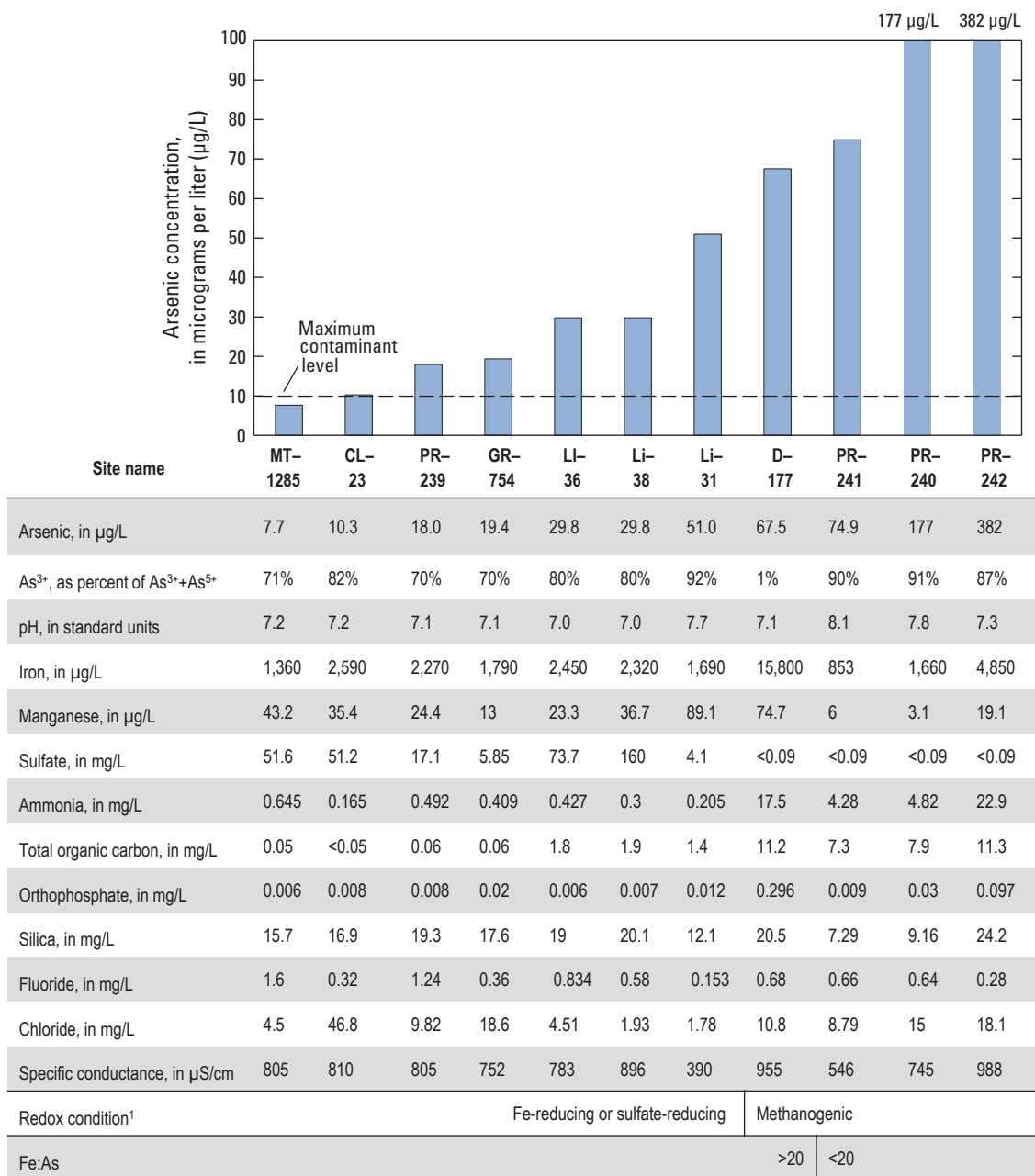
construction are not available.) Another possible explanation is that the samples were not adequately preserved at the time of sampling. Sampling protocols require that ethylenediaminetetraacetic acid (EDTA) be added to the samples in the field to preserve the concentration of species (Garbarino and others, 2012), and it is possible that the amount of EDTA was not sufficient to prevent As^{3+} from oxidizing to As^{5+} between sample collection and analysis. The fact that the arsenic speciation samples were unfiltered may have affected the analytical results.

Other Water-Quality Constituents

The EPA recommends that key water-quality constituents should be known before selection of an arsenic treatment system: arsenic, arsenic speciation, chloride, fluoride, Fe, Mn, nitrate, nitrite, phosphate, pH, silica, sulfate, total dissolved solids, and total organic carbon (U.S. Environmental Protection Agency, 2003). Concentrations of these constituents are presented in figure 2. (Ammonium is shown instead of nitrate and nitrite, which were not detected. Specific conductance (SC) is shown instead of total dissolved solids. Orthophosphate is shown instead of phosphate).

The pH of the raw water was neutral or slightly alkaline (7.1–8.1). Iron concentrations were 853–15,800 $\mu\text{g/L}$, and the median was 2,270 $\mu\text{g/L}$. All Fe concentrations were above the EPA Secondary MCL (SMCL) of 300 $\mu\text{g/L}$. Redox conditions were estimated based on concentrations of dissolved oxygen, nitrate, manganese, iron and sulfate (McMahon and Chapelle, 2008). The seven samples with the lowest arsenic concentrations (7.7–51 $\mu\text{g/L}$) were estimated to be Fe-reducing or sulfate-reducing. The four samples with the highest arsenic concentrations (67.5–382 $\mu\text{g/L}$) were estimated to be methanogenic (methane producing), which is the most reduced state. The methanogenic samples had unusually high concentrations of total organic carbon (7.3–11.3 $\mu\text{g/L}$) and ammonia (4.28–22.9 $\mu\text{g/L}$).

Also shown are Fe:Artenic ratios, a measure used as an indicator of whether Fe-removal methods are applicable for arsenic removal (U.S. Environmental Protection Agency, 2005). Three of the four methanogenic samples had Fe:Artenic ratios less than 20, which indicates that oxidation/filtration using Mn-based media may not be effective for removing arsenic.



¹Estimated using method of McMahon and Chapelle (2008).

Figure 2. Quality of raw water from 11 domestic wells in southwestern and central Ohio, 2013 [As³⁺, arsenite; As⁵⁺, arsenate; %, percent; mg/L, milligram per liter; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; Fe, iron, As, arsenic].

Types of Water-Treatment Systems Sampled

Three general types of water-treatment systems were sampled for this study. (See “Sidebar—Arsenic Treatment Terms Used in This Report” for a description of the treatment processes.)

- Single-tap reverse-osmosis systems were in use at seven sites. Two of the seven systems had not been maintained for more than 6 years at the time of sampling.
- Whole-house oxidation/filtration systems using Mn-based media were in use at two sites. Both systems included water softeners, and one system included chlorination.
- Systems that included whole-house anion exchange and single-tap reverse osmosis were in use at two sites. Both systems included water softeners and preoxidation (chlorination at one site and oxidation using Mn-based media at the second site). At one of the sites, the single-tap reverse-osmosis unit included a cartridge of Fe-based adsorptive media.

Additional details about each system are included in table 3.

Effectiveness of The Water-Treatment Systems

One measure of the effectiveness of arsenic treatment systems is whether the arsenic concentration of the final water sample is less than the MCL of 10 µg/L. Arsenic concentrations in the final samples ranged from 3.6 to 173 µg/L, and the median value was 9 µg/L. About one-half of the systems decreased the arsenic concentration to less than the MCL. A second measure of effectiveness is the percent decrease in arsenic concentrations between the raw and final samples computed as $([As_{raw} - As_{final}] / As_{raw}) * 100$. The percentage of arsenic removed by the 11 treatment systems ranged from 2 to 90 percent, and the median was 65 percent.



About 1.8 million Ohio residents use domestic wells as a source of drinking water. Photograph by Mary Ann Thomas, USGS.

Table 3. Characteristics of water-treatment systems sampled in southwestern and central Ohio, 2013.

[Numbers indicate position in treatment train. Bold text denotes component used for arsenic removal. All components are point of entry (whole house) unless denoted as point of use (single tap). POU, point of use; <, less than; EPA, U.S. Environmental Protection Agency; Mn, manganese; Fe, iron]

Site name	Components in treatment system	History		
		Age of system	Purchase and installation	Maintenance
MT-1285	1. Water softener 2. Reverse osmosis—POU	Unknown	Installed by previous homeowner	No maintenance in at least 6 years.
PR-239	1. Water softener 2. Reverse osmosis—POU	5 years	Homeowner's son	Homeowner's son.
LI-36	1. Water softener 2. Reverse osmosis—POU	<1 year	Equipment purchased at home maintenance store and installed by homeowner	None; system was new at the time of sampling.
LI-31	1. Sediment filter 2. Water softener 3. Reverse osmosis—POU	<1 year	Equipment supplied and installed by water-treatment professional.	None; system was new at the time of sampling.
D-177	1. Sediment filter 2. Water softener 3. Reverse osmosis—POU ¹	15 years	System similar to PR-241 originally installed by the EPA in 1999; homeowners later disconnected two components (anion exchange and oxidation using Mn-based media) because of cost/maintenance reasons	Professional.
PR-240	1. Sediment filter 2. Water softener 3. Reverse osmosis—POU	15 years	System similar to PR-241 originally installed by the EPA in 1999; homeowners later disconnected two components (anion exchange and oxidation using Mn-based media) because of cost/maintenance reasons	No maintenance in at least 6 years.
CL-23	1. Reverse osmosis—POU	25 years	Professional	Professional.
Oxidation/filtration using Mn-based media				
LI-38	1. Sediment filter 2. Oxidation/filtration using Mn-based media 3. Water softener	10 years	Equipment supplied and installed by a professional.	Professional.
GR-754	1. Sediment filter 2. Chlorination 3. Oxidation/filtration using Mn-based media 4. Carbon filter 5. Water softener	<1 year	Equipment purchased online and installed by homeowner	Homeowner.
Anion exchange and reverse osmosis				
PR-241	1. Sediment filter 2. Water softener 3. Oxidation using Mn-based media ¹ 4. Anion exchange 5. Reverse osmosis—POU	15 years	Installed by the EPA in 1999.	Professional.
PR-242	1. Aeration (to remove methane gas) 2. Chlorination 3. Carbon filter 4. Anion exchange 5. Water softener 6. POU unit with four cartridges: (a) Sediment filter—POU (b) Carbon filter—POU (c) Reverse osmosis—POU (d) Adsorption using Fe-based media (Fe-modified anion-exchange resin)—POU	<4 years	Installed by the EPA in 1999; system revised three times between 2004 and 2011. Fe-based adsorption cartridge added to POU reverse-osmosis system by homeowner in 2012	Homeowner.

¹Results of water-quality analysis indicate that this component was not functioning correctly.

Reverse Osmosis

At seven sites, reverse-osmosis units were installed beneath kitchen sinks to treat the water used for drinking and cooking. At six of the sites, water softeners served as pretreatment to remove elevated concentrations of Fe and Mn that can foul reverse-osmosis membranes. Sediment filters preceded the water softeners at two sites. Five of the reverse-osmosis systems were being maintained at time of sampling, and two systems had not been maintained.

Results for the five maintained systems are shown in figure 3A. For four of the systems, arsenic concentrations in the final samples were less than 10 $\mu\text{g/L}$. The percent decrease in arsenic concentrations ranged from 22 to 81 percent. For the two systems that were not maintained, the decrease in arsenic

concentration was 2–26 percent (fig. 3B). At most of the sites, As^{5+} was the predominant species in the final samples (figs. 3A and 3B).

Substantial decreases in pH, ANC, and most concentrations of cations and anions were observed in final samples from the reverse-osmosis systems (table 2). Values of SC in the raw and final samples were compared as a general indicator of whether the reverse-osmosis systems were operating correctly. Six of the systems showed SC decreases of 89 to 98 percent; however, for one system (at site D-177), the SC of the final sample was slightly higher than the raw water, which suggests that the reverse-osmosis system was not working at the time of sampling even though the homeowners described the systems as being maintained.



Reverse osmosis is typically part of a single-tap system used to treat just the water used for drinking and cooking. Photograph by Mike Ekberg, Miami Conservancy District.

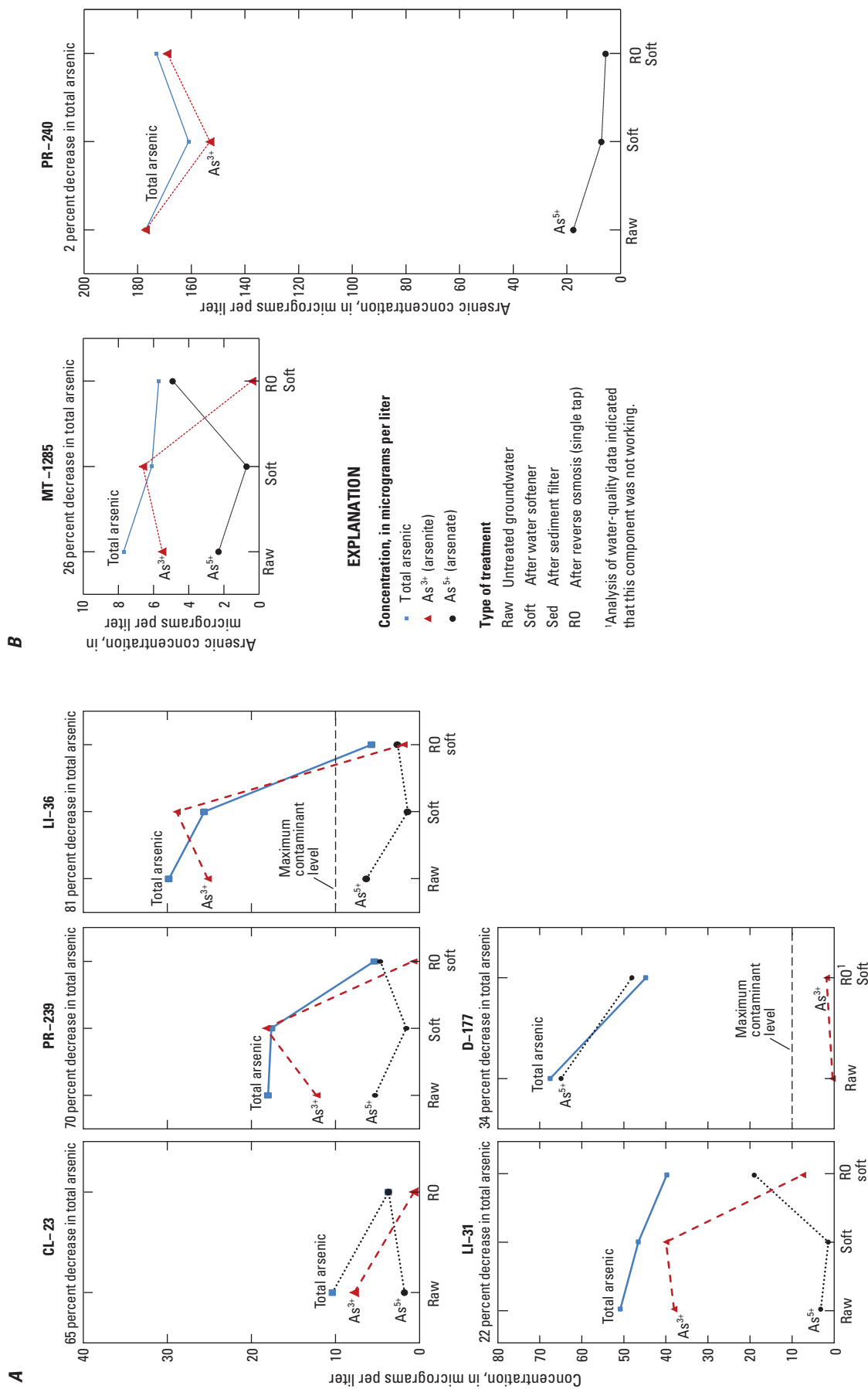


Figure 3. Effect of reverse-osmosis systems on concentrations of total arsenic, arsenite, and arsenate. *A*, Systems that had been maintained. *B*, Systems that had not been maintained.

Oxidation/Filtration Using Manganese-Based Media

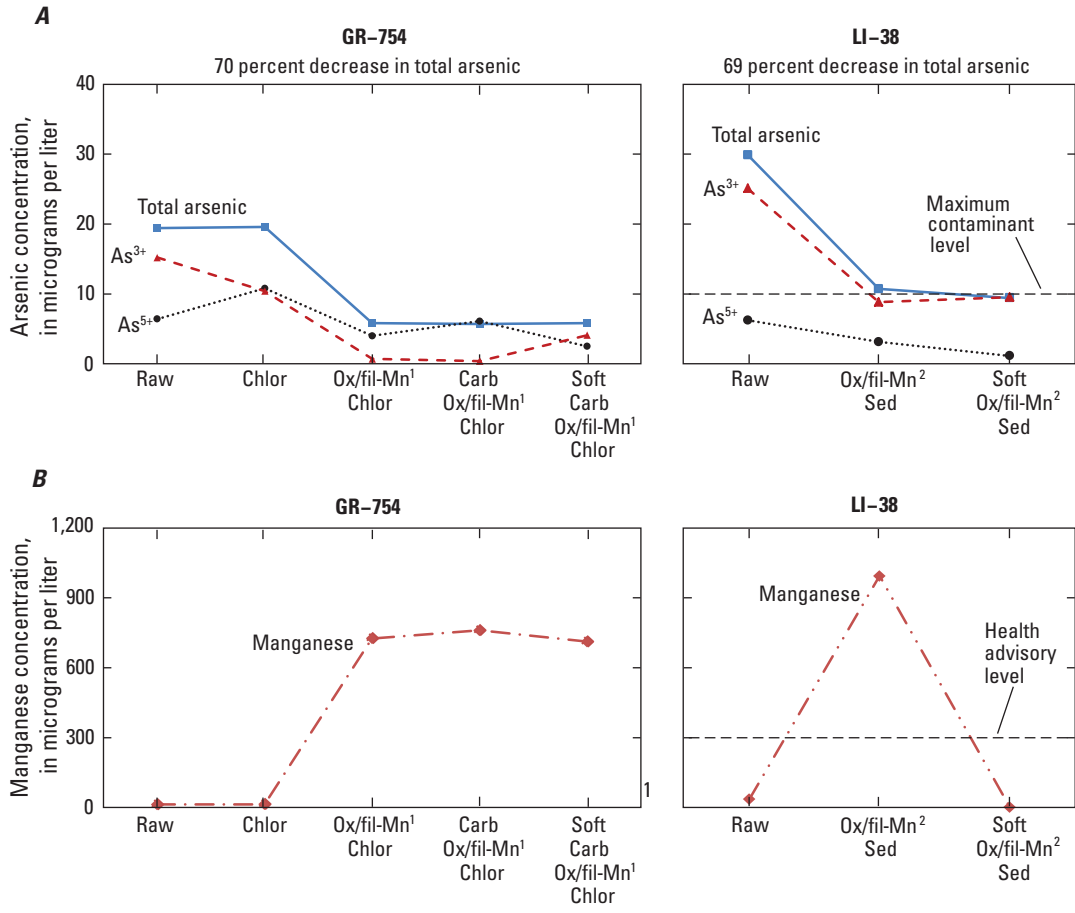
At two sites, the water-treatment systems included oxidation/filtration using solid Mn-based media (fig. 4A). At site Li-38, the system consisted of a sediment filter, oxidation/filtration using Mn-based media (Birm), and water softening. This system decreased the arsenic concentration by 69 percent from 29.8 to 9.3 $\mu\text{g/L}$. At site GR-754, the system included chlorination, oxidation/filtration using Mn-based media (Greensand Plus), carbon filtration, and water softening. This system decreased the arsenic concentration by 70 percent from 19.4 to 5.8 $\mu\text{g/L}$.

At both sites, concentrations of Mn increased greatly after treatment by the oxidation/filtration component of the system (fig. 4B). Concentrations of Mn of 13.0 and 36.7 $\mu\text{g/L}$ in raw water increased to 726 and 997 $\mu\text{g/L}$, respectively, after oxidation/filtration using Mn-based media. At Li-38, the

elevated Mn was removed by the water softener before being consumed by the homeowners. At GR-754, the final sample collected from the kitchen tap had a Mn concentration of 712 $\mu\text{g/L}$, which is well above the EPA lifetime health advisory of 300 $\mu\text{g/L}$ and the secondary MCL (based on esthetic criteria such as staining) of 50 $\mu\text{g/L}$ (U.S. Environmental Protection Agency, 2009). It is not known why this high concentration of Mn was not removed by the water softener. The supplier of the water-treatment system advised the homeowner that the problem could be fixed by increasing the amount of chlorine used in the preoxidation step. An increase in Mn concentration of treated water was also observed in the EPA pilot-scale study at the Licking County High School (discussed in “Previous Studies”). At this site, the system required multiple revisions to try to maintain low concentrations of arsenic and Mn in the treated water (U.S. Environmental Protection Agency, 2011).



Oxidation/filtration is typically part of a whole-house treatment system installed in the basement of a home. Photograph by Mike Ekberg, Miami Conservancy District.



EXPLANATION

Concentration, in micrograms per liter	Type of treatment
■ Total arsenic	Raw Untreated groundwater
▲ As ³⁺ (arsenite)	Chlor After chlorination
● As ⁵⁺ (arsenate)	Carb After carbon filter
◆ Manganese	Soft After water softener
	Sed After sediment filter
	Ox/fil-Mn After oxidation/filtration using manganese-based media
	¹ Greensand Plus
	² Birm

Figure 4. Effect of oxidation/filtration systems on concentrations of selected constituents. *A* Total arsenic, arsenite and arsenate. *B*, Manganese.

Systems That Include Anion Exchange and Reverse Osmosis

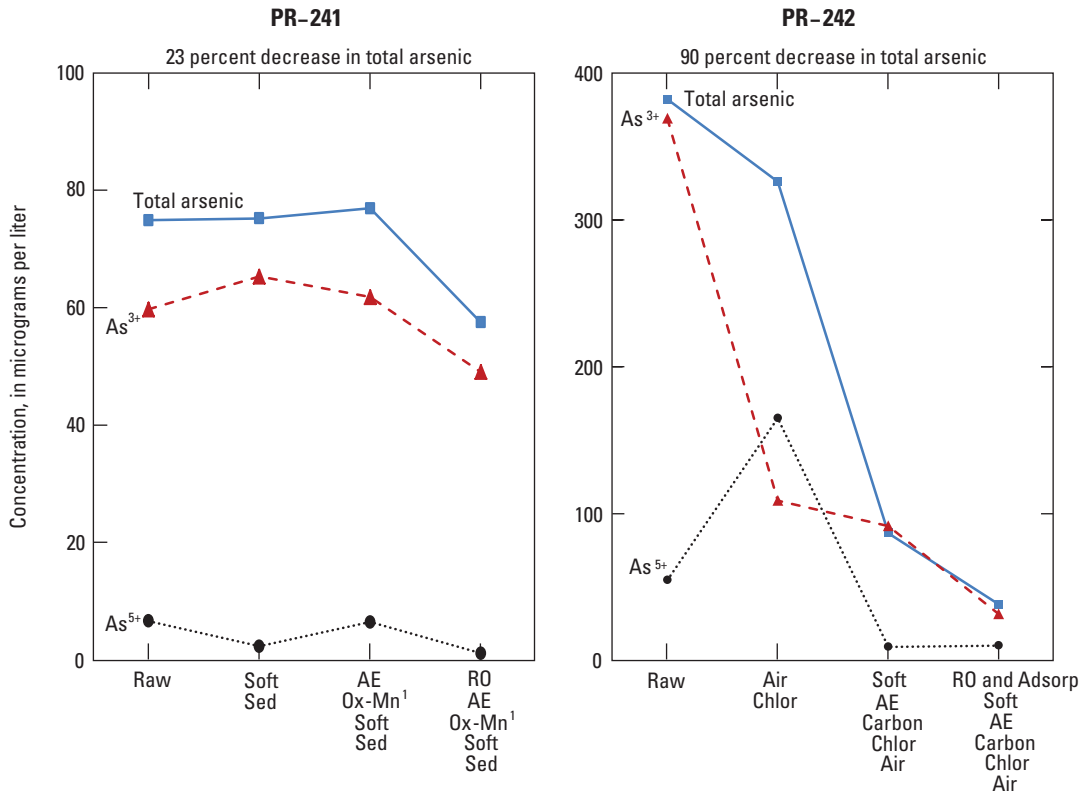
At two sites, the treatment systems included whole-house anion exchange and single-tap reverse osmosis (fig. 5). At site PR-241, the treatment system included a sediment filter, a water softener, preoxidation using Mn-based media (Filox), anion exchange, and single-tap reverse osmosis. The system decreased the arsenic concentration by 23 percent from 74.9 to 57.5 $\mu\text{g/L}$. The reason for the relatively low effectiveness of this system could not be determined because samples were not collected after each treatment step. Personnel from EPA resampled the system in November, 2013, and concluded that the component for preoxidation using Mn-based media was not working (Thomas Sorg, U.S. Environmental Protection

Agency, 2015, written commun.). Anion exchange only removes As^{5+} , so without preoxidation of As^{3+} to As^{5+} , anion exchange was not effective.

At site PR-242, the treatment system included aeration to remove methane gas, preoxidation by chlorination, carbon filtration, water softening, anion exchange, and a single-tap unit that included cartridges for reverse osmosis and adsorptive using Fe-based media (Fe-modified anion exchange resin). The arsenic concentration of the raw water was 382 $\mu\text{g/L}$. After treatment, the concentration decreased by 90 percent, to 38.4 $\mu\text{g/L}$. Anion exchange removed most of the As^{5+} , and caused a decrease in the arsenic concentration from 326 to 86.8 $\mu\text{g/L}$. After the single-tap unit with cartridges for reverse osmosis and Fe-based adsorption, the arsenic concentration was decreased by 56 percent from 86.8 to 38.4 $\mu\text{g/L}$.



Some arsenic treatment systems can be relatively complex. Pre-oxidation is needed to convert As^{3+} to As^{5+} prior to removal by anion exchange. Photograph by Mike Ekberg, Miami Conservancy District.



EXPLANATION

Concentration, in micrograms per liter

- Total arsenic
- ▲ As³⁺ (arsenite)
- As⁵⁺ (arsenate)

Type of treatment

- Raw Untreated groundwater
- Air After aeration to remove methane
- Chlor After chlorination
- Carb After carbon filter
- Soft After water softener
- Sed After sediment filter
- Ox-Mn¹ After oxidation using manganese-based media (Filox)
- AE After anion exchange
- RO After reverse osmosis (single tap)
- Adsorb After adsorption using iron-based media (single tap)

¹Analysis of water-quality data indicated this component was not working.

Figure 5. Effect of systems that include anion exchange and reverse osmosis on concentrations of total arsenic, arsenite and arsenate.

Effects of Methods Used for Pretreatment

Water softening.—Water softeners, which employ cation exchange, are used as a form of pretreatment to remove high concentrations of Fe and Mn that can foul media or membranes in arsenic removal units. The effect of water softeners alone was investigated using data from six of the maintained systems. Results indicate that a small (2–34 percent) decrease in total arsenic concentrations happened after softening. There is some indication that softening increased the proportion of As^{3+} in the water, but the differences are small relative to the variability of the arsenic speciation data.

Chlorination.—Two water-treatment systems included chlorination. Results indicate that chlorination oxidized some but not all of the As^{3+} in the raw water. At site GR-754, the percentage of As^{3+} decreased from 70 percent in raw water to 49 percent in chlorinated water. At site PR-242, the percentage of As^{3+} decreased from 87 percent in raw water to 40 percent in chlorinated water.

Chlorination of water with high concentrations of organic carbon can create DBP, but these compounds were not analyzed. The four samples with the highest raw arsenic concentrations had very high concentrations of total organic carbon, so formation of DBPs is a possible concern.

Oxidation using Mn-based media.—At one site, oxidation using Mn-based media (Filox) was used to oxidize As^{3+} to As^{5+} before anion exchange. The preoxidation component was effective when it was first installed in 1998, but it was not working in 2013 at the time of this study. The same oxidation/filtration media was used successfully at public-water systems; however, the backwash process used to regenerate the media requires water pressures of 23–30 gallons per minute (gal/min), which may not be feasible at most homes (Wang and others, n.d.).

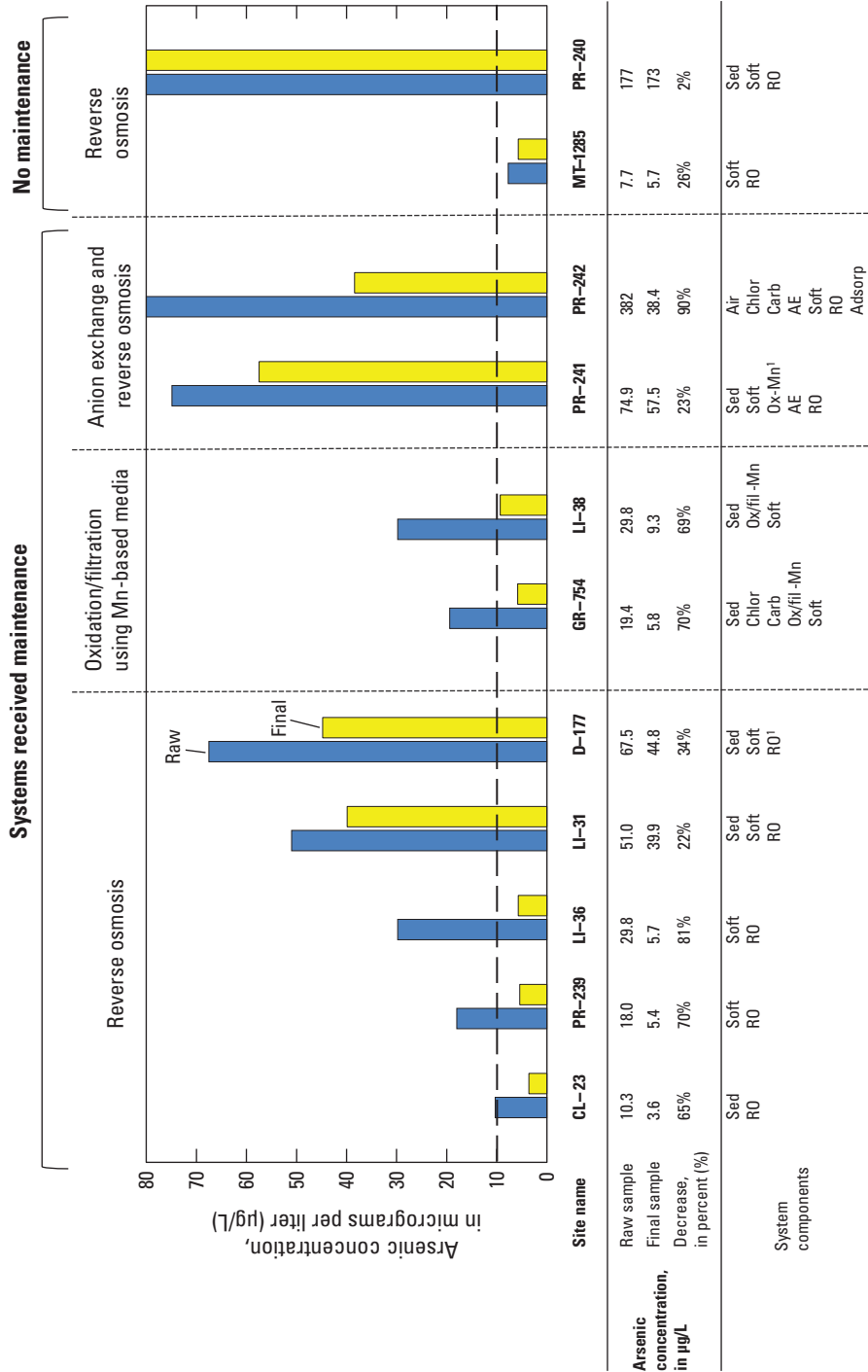
Factors Related To Effectiveness of Arsenic Removal

Based on the data from this study, it is not possible to determine which type of arsenic treatment system is most effective because the number of sites sampled is small relative to the variation among the sites in terms of (1) methods of treatment and pretreatment, (2) age and maintenance history of the systems; and (3) arsenic concentrations and other chemical characteristics of the raw water. Despite the wide range of variability, the data show some broad relations between effectiveness of arsenic removal, characteristics of the treatment systems, and the quality of the raw water.

Characteristics of Treatment Systems

Arsenic concentrations in raw and final water samples were compared to two characteristics of the treatment systems—the system type and maintenance history (fig. 6). There is no clear relation between the system type and the effectiveness of arsenic removal; for example, the percentage of arsenic removed by five reverse-osmosis systems ranged from 22 to 81 percent. On the other hand, there is a general relation between system maintenance and effectiveness of arsenic removal. It is not surprising that the nine systems that received maintenance were generally more effective (22–90 percent decrease in arsenic) than the two systems that had not been maintained in several years (2–26 percent decrease).

In addition, for two of the systems that received maintenance (D-177 and PR-241), analysis of water-quality data indicates that a component of the treatment system was not working, unbeknownst to the homeowner (discussed in “Reverse Osmosis” and “Anion Exchange and Reverse Osmosis” sections). These systems also had low effectiveness (23–34 percent removal). But maintenance is not the only factor related to system effectiveness; one of the lowest arsenic removal percentages (22 percent) was from a relatively new system (about six months old) installed by a water-treatment professional.



¹Analysis of water-quality data indicated this component was not working.

Figure 6. Arsenic removal in relation to system type and maintenance history for 11 sites in southwestern and central Ohio, 2013.

Raw-Water Quality

For the nine sites that received maintenance, system effectiveness was compared to the arsenic concentration of the raw water. At sites with raw-water arsenic concentrations of 10–30 $\mu\text{g/L}$ (fig. 7A), the treatment systems removed 65–81 percent of the arsenic, and the final arsenic concentrations were less than the MCL of 10 $\mu\text{g/L}$. Similar results were observed from two different types of systems—single-tap reverse osmosis and whole-house oxidation/filtration using Mn-based media.

On the other hand, for the three sites with raw-water arsenic concentrations of 50–75 $\mu\text{g/L}$ (fig. 7B), the effectiveness of the treatment systems was lower; the systems removed 22–34 percent of the arsenic in the raw water, and arsenic concentrations in the final samples were greater than the MCL (fig. 7).

Other chemical characteristics of the raw water may contribute to differences in treatment effectiveness that are shown in 7A and B. In general, the five samples with lower arsenic concentrations (10–30 $\mu\text{g/L}$) also had relatively lower pH (7.0–7.2), lower concentrations of organic carbon (less than 0.05–1.9 milligrams per liter [mg/L]) and ammonia (0.165–0.492 mg/L), and the redox conditions were classified as Fe- or sulfate-reducing. In contrast, the three samples with higher arsenic concentrations (50–75 $\mu\text{g/L}$) had higher or more varied pH (7.1–8.1), and concentrations of organic carbon (1.4–11.2 mg/L), and ammonia (0.205–17.5 mg/L), and the redox condition of two of the three samples was classified as methanogenic. One or more of these factors can influence the performance of the arsenic treatment processes (U.S. Environmental Protection Agency, 2003).

One site did not fit the general trend of decreased effectiveness at higher raw-water arsenic concentrations (fig. 7C). At site PR-242, the raw-water arsenic concentration was very high (382 $\mu\text{g/L}$), and the effectiveness of the treatment system was also high (90 percent). Despite this, the arsenic concentration of the final sample (38.4 $\mu\text{g/L}$) was still substantially

greater than the MCL. Site PR-242 was atypical in several ways. One is that the treatment system was designed, installed, monitored, and maintained as part of an EPA research program. Between 2004 and 2011, the system was revised three times, and, as a result, the resources devoted to this treatment system were unusually high. As an indication of this, one of the conclusions of the final report was that drilling a new well to an aquifer with lower arsenic concentrations was a low-cost option that warrants consideration (Wang and others, n.d.).

A second reason that site PR-242 is atypical is that the raw-water arsenic concentration was very high compared to other wells sampled in southwestern and central Ohio (Miami Conservancy District, 2011; Thomas and others, 2005, 2008; Shindel and others, 2000; Dumouchelle, 1999). The next-highest arsenic concentration reported for Ohio is 225 $\mu\text{g/L}$, which was detected in a domestic well in southeastern Ohio (Petty, 2000). Sampling for arsenic has been relatively limited, so higher concentrations may exist in areas that have not been sampled; however, available data indicate that arsenic concentrations similar to 382 $\mu\text{g/L}$ may be uncommon in Ohio groundwater.

Results of arsenic studies in southwestern and central Ohio indicate that most (80 percent) of the elevated arsenic concentrations detected in domestic wells range from 10 to 30 $\mu\text{g/L}$, and redox conditions are Fe- or sulfate-reducing (Shindel and others, 2000; Thomas and others, 2005; Thomas, 2016). In other words, 80 percent of samples may be somewhat similar to the five samples in figure 7A in terms of raw-water quality. Groundwater with higher arsenic concentrations (about 40–70 $\mu\text{g/L}$) and methanogenic redox conditions were less common but should be expected especially in the vicinity of buried valleys (Thomas and others, 2005; Thomas, 2016). Results of the current study suggest that, for these types of groundwater, it may be difficult to reduce arsenic concentrations to less than the MCL using water-treatment methods available to homeowners; however, additional study may be needed to confirm or disprove this idea.



Domestic wells in Ohio are not routinely tested for arsenic. Photograph by Mike Ekberg, Miami Conservancy District.

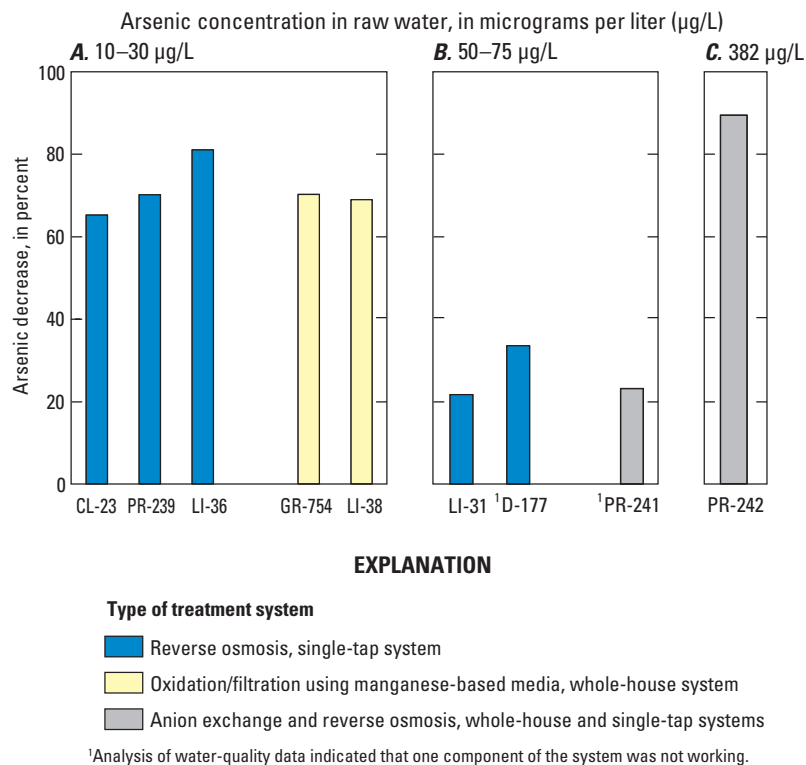


Figure 7. Arsenic removal in relation to system type and raw-water arsenic concentrations for nine maintained systems in southwestern and central Ohio, 2013 with different ranges of raw-water arsenic concentrations. A, 10–30 $\mu\text{g/L}$. B, 50–75 $\mu\text{g/L}$. C, 382 $\mu\text{g/L}$.

Summary of Results

In 2013, the U.S. Geological Survey and the Miami Conservancy District investigated the effectiveness of arsenic-treatment methods used at 11 homes in southwestern and central Ohio. Unfiltered samples of raw and treated water were collected from each home and analyzed for arsenic, arsenic species, major ions, trace elements, nutrients, and total organic carbon. Information about the type, age, and maintenance history of the treatment systems was provided by the homeowners.

The untreated (raw) groundwater had arsenic concentrations of 7.7–382 micrograms per liter ($\mu\text{g/L}$), and the median concentration was about 30 $\mu\text{g/L}$. The raw water was neutral to slightly alkaline (pH of 7.0–8.1) and strongly reducing, as indicated by high concentrations of iron. Arsenite (As^{3+}) was the predominant species in 10 of the 11 raw water samples.

The treatment systems included (1) seven single-tap reverse-osmosis systems, (2) two whole-house oxidation/filtration systems using manganese (Mn)-based media, and (3) two systems that included whole-house anion exchange and single-tap reverse osmosis. All but one system included pretreatment by a water softener, and two systems included preoxidation to

convert arsenite (As^{3+}) to arsenate (As^{5+}) before treatment by anion exchange.

None of the treatment systems removed all of the arsenic in the raw water. About one-half of the systems decreased the arsenic concentrations to less than the maximum contaminant level of 10 $\mu\text{g/L}$. The amount of arsenic removed by the 11 systems varied greatly, from 2 to 90 percent.

It was not possible to determine if one type of system was more effective than another because the sample size was small relative to the variation among the systems with respect to system configuration, pretreatment methods, maintenance history, and raw-water quality. However, the data indicate that arsenic removal is broadly related to two general factors—system maintenance and raw-water quality.

At some sites, the low effectiveness of arsenic removal may have been related to system maintenance and (or) operation issues. At two sites, homeowners acknowledged that the treatment systems had not been maintained for several years. At two other sites, the treatment systems were being maintained, but analysis of the water-quality data indicated that one of the components was not working, unbeknownst to the homeowner. EPA research at a small number of sites in Ohio indicated that operation and maintenance of some arsenic-treatment systems was not always simple.

Another factor related to system effectiveness was the quality of the raw water. Among the maintained systems, treatment methods were less effective at removing higher concentrations of arsenic. For sites with raw-water concentrations of 10–30 µg/L, the systems decreased arsenic concentrations by 65–81 percent, and arsenic concentrations in the treated water were less than the MCL of 10 µg/L. For sites with higher raw-water arsenic concentrations (50–75 µg/L), the arsenic decrease was 23–34 percent, and concentrations in the treated water were 4–5 times higher than the MCL. Other characteristics of the raw water may have affected the performance of treatment systems; in general, raw water with the higher arsenic concentrations also had higher pH, higher concentrations of organic carbon and ammonia, and more reducing (methanogenic) redox conditions.

One system clearly did not fit the general trend of decreased effectiveness at higher raw-water arsenic concentrations. At site PR-242, concentration of arsenic in the raw water was very high (382 µg/L), and the treatment system decreased it by 90 percent. Despite this large decrease, the arsenic concentration of the final water (38.4 µg/L) was substantially greater than the MCL. The treatment system at this site was unusual because it was installed, monitored and revised over 7 years as part of the U.S. Environmental Protection Agency research program. The site was also atypical because the raw-water arsenic concentration was much greater than other concentrations measured in domestic wells of southwestern and central Ohio.

For sites with raw-water arsenic concentrations of 10–30 µg/L, two types of systems (single-tap reverse osmosis and whole-house oxidation/filtration) produced similar results in terms of arsenic removal, but the quality of the treated water differed in other respects. Reverse osmosis caused substantial decreases in pH, alkalinity, and most ions in the treated water. On the other hand, oxidation/filtration using Mn-based media caused a large increase of Mn concentrations, from less than 50 µg/L in raw water to more than 700 µg/L in outflow from the oxidation/filtration units.

One of the limitations of this study is that the number of sites is small relative to the variation among sites in terms of the system type, age and maintenance of the system, water use, and the chemical composition of the raw water. However, the results of this study indicate that additional investigation may be warranted to determine which methods of arsenic removal are effective/practical for residential use in areas like Ohio, where groundwater with elevated arsenic concentrations is strongly reducing, and the predominant arsenic species is arsenite (As³⁺).

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Table 2

26 The Effectiveness of Water-Treatment Systems for Arsenic Used in 11 Homes in Southwestern and Central Ohio, 2013

Table 2. Water-quality results from 11 domestic wells in southwestern and central Ohio, 2013.

Table 2 is an Excel file that can be accessed at <http://dx.doi.org/10.3133/sir20155156>.

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