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Associations between private well water and community water supply arsenic concentrations in the conterminous United States

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Abstract

Geogenic arsenic contamination typically occurs in groundwater as opposed to surface water supplies. Groundwater is a major source for many community water systems (CWSs) in the United States (US). Although the US Environmental Protection Agency sets the maximum contaminant level (MCL enforceable since 2006: 10 μg/L) for arsenic in CWSs, private wells are not federally regulated. We evaluated county-level associations between modeled values of the probability of private well arsenic exceeding 10 μg/L and CWS arsenic concentrations for 2,231 counties in the conterminous US, using time invariant private well arsenic estimates and CWS arsenic estimates for two time periods. Nationwide, county-level CWS arsenic concentrations increased by 8.4 μg/L per 100% increase in the probability of private well arsenic exceeding 10 μg/L for 2006 – 2008 (the initial compliance monitoring period after MCL implementation), and by 7.3 μg/L for 2009 – 2011 (the second monitoring period following MCL implementation) (1.1 μg/L mean decline over time). Regional differences in this temporal decline suggest that interventions to implement the MCL were more pronounced in regions served primarily by groundwater. The strong association

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Credit Author Statement:
Maya Spaur: Methodology, Software, Formal Analysis, Writing-Original Draft, Visualization. **Melissa A. Lombard:** Methodology, Conceptualization, Resources, Writing-Review & Editing, Supervision. **Joseph D. Ayotte:** Conceptualization, Resources, Writing-Review & Editing. **David E. Harvey:** Writing-Review & Editing. **Benjamin C. Bostick:** Writing-Review & Editing. **Steven N. Chillrud:** Writing-Review & Editing. **Ana Navas-Acien:** Conceptualization, Writing-Review & Editing, Supervision. **Anne E. Nigra:** Methodology, Conceptualization, Resources, Writing-Review & Editing, Supervision.

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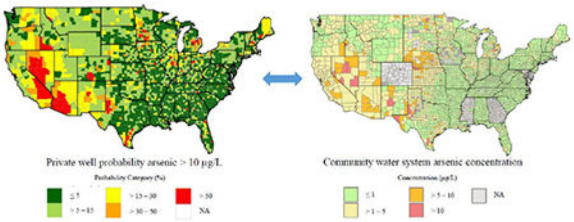
SUPPORTING INFORMATION:
The Supporting Information includes tables and figures; county descriptive statistics; linear regression coefficients; maps of the predicted probabilities.

Declaration of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

between private well and CWS arsenic in *Rural, American Indian*, and *Semi Urban, Hispanic* counties suggests that future research and regulatory support are needed to reduce water arsenic exposures in these vulnerable subpopulations. This comparison of arsenic exposure values from major private and public drinking water sources nationwide is critical to future assessments of drinking water arsenic exposure and health outcomes.

Graphical abstract



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1. Introduction

1.1 Background

Arsenic-contaminated drinking water is a major concern for United States (US) residents served by public water systems exceeding the current US Environmental Protection Agency (EPA) maximum contaminant level (MCL) of 10 µg/L (Foster, 2019; United States Environmental Protection Agency, 2018), and for approximately 40 million US residents reliant on private wells, which are not subject to EPA regulation and defined as serving less than 15 service connections and less than 25 people (Dieter, 2018; Johnson, 2019; Maupin, 2018). To protect human health, the EPA passed the Final Arsenic Rule in 2001 which lowered the MCL from 50 µg/L to 10 µg/L and became enforceable in 2006 (United States Environmental Protection Agency, 2001; United States Environmental Protection Agency, 2004). The first two compliance monitoring periods for the Final Arsenic Rule were 2006 - 2008 and 2009 - 2011. All public water systems, including community water systems (CWSs, serving at least 15 service connections or 25 people year-round), must comply with the EPA MCL. Private wells (typically serving individual households) are not federally regulated and well owners are responsible for testing, treating, and maintaining appropriate treatment systems (United States Environmental Protection Agency, 2020b).

Nationwide, approximately 85.5% of CWSs use groundwater sources, although more people in the US are serviced by CWSs using surface water.(Nigra, 2020b; United States Environmental Protection Agency, 2008). Average arsenic concentrations in CWSs at the county-level were recently estimated using over 290,000 compliance monitoring records from the EPA National Contaminant Occurrence database supporting the third Six Year Review (SYR) database from 2006 to 2011 (Nigra, 2020b). An estimated 1.5% of CWSs (n=397 of 26,895) had three-year average arsenic concentrations over 10 µg/L in 2006 - 2008 compared to less than 1% (n=159) in 2009 – 2011 (Nigra, 2020b). CWSs continuing to exceed the arsenic MCL served smaller populations (<500 people), were more likely reliant on groundwater, and were more likely located in the Southwestern US, where geological characteristics – including alkaline, saline, and oxidizing conditions – contribute to higher

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groundwater arsenic concentrations (Ayotte, 2017; Foster, 2019; Nigra, 2020b). Other studies also support that MCL compliance is related to the size of the population served, region, and the median income of the population served by the CWS (Alfredo, 2014; Foster, 2019; McGavisk, 2013). Arsenic concentrations in private wells have been measured by the US Geological Survey for various purposes and are available from the National Water Information System (NWIS) database (United States Geological Survey, 2020). These data were used to build models to estimate the probability of arsenic concentrations in private wells exceeding regulatory limits (Lombard, 2021b), including 10 μg/L, 5 μg/L (the current MCL for New Jersey and for New Hampshire, beginning in July 2021), and 1 μg/L (the MCL goal for the Netherlands and similar to the EPA MCL goal of 0 μg/L) (Ahmad, 2020; National Research Council, 2001; New Hampshire Department of Environmental Services, 2018; New Jersey Department of Environmental Protection, 2020; United States Environmental Protection Agency, 2018).

1.2 Rationale

The association between private well and CWS arsenic concentrations has not been evaluated at the national scale since the implementation of the EPA Final Arsenic Rule. This association may be critical in determining the effectiveness of interventions to reduce arsenic exposure in CWSs in areas where groundwater aquifers have high arsenic concentrations. One early study compared groundwater arsenic concentrations from CWSs to other wells including private drinking water wells and observation wells (Focazio, 2000). Arsenic concentrations in public water supply wells tended to be lower than in the other wells; this was attributed in part to the ability of CWSs to locate water supplies in areas with low arsenic, whereas private well locations are constrained by property boundaries and economic considerations (Focazio, 2000). Other differences between CWS and private well arsenic concentrations arise because they are drawn from different geologic environments, aquifers, or aquifer regions (Bruce, 2001; Erickson, 2005; Levitt, 2019). For example, in New Hampshire, many CWSs obtain water from shallow, highly-productive glacial deposit aquifers, whereas private wells are primarily drilled into the underlying fractured crystalline bedrock (Levitt, 2019). The probability of arsenic exceeding 10 μg/L in private wells throughout the US tends to be highest in New England, the upper Midwest region, and in the Southwest (Ayotte, 2017; DeSimone, 2009; Lombard, 2021b). CWSs reliant on groundwater aquifers in these regions likely have higher arsenic concentrations than those in regions with low groundwater arsenic. In regions where similar aquifers serve private wells and CWSs, high levels of arsenic in private wells may indicate high arsenic exposures from groundwater supplies to CWSs. Private well arsenic may be similar to CWS arsenic particularly where groundwater aquifers serving CWSs and private wells are similar. Quantifying the association between private well arsenic and CWS arsenic across the US and over time following the EPA's Final Arsenic Rule can quantify the contribution of groundwater arsenic to CWS arsenic, and can inform additional programs that focus on reducing water arsenic for private well users who remain unprotected.

1.3 Objectives

Our objectives were 1) to evaluate the association between the probability of private well arsenic exceeding the MCL of 10 μg/L and arsenic concentrations measured in CWSs across

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the conterminous US at the county level and 2) to identify subgroups where private well arsenic is more strongly associated with CWS arsenic concentrations at the county level. This study is important for public health because understanding the association between private well water arsenic and CWS arsenic may support the use of private well arsenic as a surrogate for groundwater arsenic exposures pre-treatment under certain conditions, such as in specific regions where private wells and CWSs source water from similar groundwater supplies. We compared the probability of private well arsenic exceeding 10 µg/L (as previously modeled by Lombard et al. (Lombard, 2021b)) to population weighted average water arsenic concentrations in CWSs (as previously derived from EPA SYR database in Nigra et al. (Nigra, 2020b)). We further stratified analyses by region, sociodemographic county-cluster, majority public water system source type, and Final Arsenic Rule compliance monitoring period (2006 - 2008 vs. 2009 - 2011). We hypothesized that the association would be stronger in 2006 - 2008 compared to 2009 – 2011, as CWSs may have reduced arsenic concentrations in the second period to ensure compliance with the 2006 MCL (via water treatment or switching/mixing source water) (United States Environmental Protection Agency, 2020a). We also hypothesized that the association would be stronger for counties where CWSs relied heavily on groundwater instead of surface water, and would differ spatially, reflecting regional differences in aquifer characteristics.

The association between private well water arsenic with CWS arsenic may have decreased over time as CWSs implemented treatment systems or changed water sources to become compliant with the 10 µg/L MCL, assuming no concomitant change in arsenic treatment by private well users as previously reported (Nigra, 2017; Welch, 2018). There is a critical need to assess the association between drinking water arsenic exposures in unregulated private wells and regulated CWSs nationwide to identify vulnerable subpopulations and counties with the greatest discrepancies in water arsenic exposure between CWS and private well users, as private well owners in these areas could lower water arsenic exposure by either connecting to a CWS or through private well treatment. These discrepancies may also vary by geographic region and sociodemographic characteristics. Additionally, identifying counties with high CWS arsenic concentrations from groundwater can target interventions to assist CWSs in reaching current and more health protective MCLs. Finally, these findings aim to inform future research and mitigation needs for populations reliant on groundwater contaminated by arsenic.

2. Methods

2.1 Private well water estimates of exceeding arsenic concentration thresholds

We utilized county-level probabilities of private well arsenic exceeding regulatory limits that were previously developed and described in detail by Lombard et al. (Lombard, 2021a; Lombard, 2021b). Briefly, the probability of arsenic exceeding 1, 5, and 10 µg/L was estimated in private wells throughout the conterminous US using boosted regression tree models (Lombard, 2021b). These models are based on the largest database of private well arsenic samples collected in the United States, which contains over 20,000 private supply well samples collected and analyzed for arsenic between 1970 and 2013 (Lombard, 2021b). Because prior studies support that private well users did not reduce water arsenic exposure

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following the EPA's MCL change (Nigra, 2017; Welch, 2018), contemporary arsenic concentrations in private wells are likely similar to concentrations measured throughout the data collection period. Predictors of groundwater arsenic concentrations were assigned to each well, including geologic (e.g., bedrock geology, rock type), geochemical (e.g., sediment geochemistry), hydrologic (e.g., groundwater recharge, percent tile drainage), and climatic (e.g., precipitation) variables (Lombard, 2021b). Using these predictors, the models were then applied to 1km^2 grids of the predictor variables to produce maps of the probability of private well arsenic exceeding 1, 5, and 10 µg/L for the conterminous US. Probability estimates from the 1km^2 grids were then grouped to the county level. For the main analysis, we used the county-level 90th percentile (high) probability estimates of private well water arsenic (wAs) exceeding 10 µg/L (hereafter referred to as "high probability wAs > 10 µg/L"). We selected the 90th percentile as the primary metric to capture variability and high exposure areas across all counties.

2.2 CWS arsenic estimates

We utilized county-level population-weighted estimates of arsenic in CWSs that were previously developed using the EPA National Contaminant Occurrence database supporting the third Six Year Review (SYR) covering years 2006 - 2011, as previously described in detail (Nigra, 2020a; Nigra, 2020b). The SYR database contains routine compliance monitoring records that were voluntarily reported by states and primacy agencies to the EPA (Nigra, 2020b; United States Environmental Protection Agency, 2016). Briefly, water arsenic concentrations at the CWS-level were averaged within three-year periods (2006 - 2008 and 2009 - 2011) and for the overall six-year period (2006 - 2011) (Nigra, 2020b). Three-year averages account for the EPA Standardized Monitoring Framework requirements for arsenic (at minimum, CWSs are required to monitor for arsenic once every three years) and match the Final Arsenic Rule compliance monitoring periods (2006 - 2008 and 2009 - 2011) (United States Environmental Protection Agency, 2004). Average water arsenic concentrations at the county-level were calculated by weighting the average arsenic concentration at each CWS by the size of the population served. CWSs were assigned to counties based on data reported in the EPA Safe Drinking Water Information System database (United States Environmental Protection Agency, 2017b).

2.3 Additional county-level covariates

We obtained estimates for total population served by public water systems or private wells (referred to as domestic, self-supplied) in 2010 (Maupin, 2014; United States Geological Survey, 2010). We classified counties by the percent of the population using public water systems in 2010 into the following four groups: ≤10%, >10-30%, >30-50%, and >50% population served by public water systems. We also used estimates of freshwater withdrawals (in million gallons per day) from ground and surface water sources within a given county to classify counties by the source water type utilized by public water systems (Maupin, 2014). Counties were classified as "Majority surface water" or "Majority ground water" when greater than 50% of public drinking water systems within a county relied on surface or ground water supplies, respectively.

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Region groupings were based on maps of neighboring states that had similar three-year average CWS arsenic concentrations (Nigra, 2020b). The regions are defined as: Central Midwest (ND, SD, NE, KS, MO), Eastern Midwest (WI, IL, IN, MI, OH, MN, IA), Mid-Atlantic and southern New England (PA, MD, DC, DE, NY, NJ, CT, RI; hereafter referred to as Mid-Atlantic), Northern New England (MA, VT, NH, ME; hereafter referred to as New England), Pacific Northwest (WA, OR, MT, WY, and ID), Southeast (OK, AR, LA, MS, AL, FL, GA, TN, KY, SC, NC, VA, WV), and Southwest (CA, NV, UT, CO, AZ, NM, TX).

Sociodemographic county-cluster groupings were previously developed by others using k-means cluster analysis to identify counties with similar sociodemographic characteristics and enable the direct comparison of health outcomes within county-clusters (Wallace, 2019). County-clusters were identified by the following sociodemographic characteristics: percentage of the county categorized as rural, race and ethnicity, educational attainment, age, sex, marital status, employment status, and health insurance status (Wallace, 2019). Using these characteristics, eight distinct county clusters were identified and characterized as *Rural, High Socioeconomic Status* (SES); *Semi Urban, High SES; Young, Urban, Mid/High SES; Mostly Rural, Mid SES; Rural, Mid/Low SES; Semi Urban, Mid/Low SES; Semi Urban, Hispanic*; and *Rural, American Indian* (Wallace, 2019).

2.4 Descriptive analyses

All statistical analyses were conducted at the county level. Data management and analysis were conducted in R version 3.6.1 and maps were created using the ggmap and mapdata packages (Becker, 2018; Kahle, 2013; OpenStreetMap contributors; R core team). We merged the high probability wAs > 10 μg/L (via Lombard et al. (Lombard, 2021b)), average three- and six- year CWS arsenic concentrations (via EPA SYR database (Nigra, 2020b)), sociodemographic county-cluster identifiers (via Wallace et al. (Wallace, 2019)) and water use estimates (via Maupin et al. (Maupin, 2014; United States Geological Survey, 2010)). One county with an extreme outlier value of 120.26 μg/L (likely a data entry error) in CWS arsenic concentration was excluded from analyses as it was above the 99th percentile of CWS arsenic concentrations. We first evaluated the 50th, 75th, and 95th percentile of average CWS arsenic concentrations nationwide and stratified by major subgroups (region, sociodemographic county-cluster, and the percent of county population served by public water systems). Similarly, we evaluated the 50th, 75th, and 95th percentile of the high probability wAs > 10 μg/L both nationwide and stratified by these major subgroups. We also determined the number and percentage of counties with high probability wAs > 10 μg/L of ≤5, >5 - 15, >15 - 30, >30 - 50, and >50% nationwide and stratified by these major subgroups.

2.5 Linear association between probability of private well water arsenic exceedance of regulatory thresholds and average CWS arsenic concentrations

We estimated the association between average CWS arsenic concentrations and high probability wAs > 10 μg/L via linear regression using the ‘lm’ function in R. Visual inspection of the residuals and fitted values was conducted before applying linear regression. We regressed average CWS arsenic concentrations on high probability wAs > 10 μg/L (continuous variable). Effect estimates represent the average change in CWS arsenic

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concentrations per 100% increase (one unit change) in high probability wAs > 10 μg/L. When divided by 10, this effect estimate can also be interpreted as the change in average CWS arsenic concentrations per 10% increase in high probability wAs > 10 μg/L. We also regressed average CWS arsenic concentrations on the categorical high probability wAs > 10 μg/L (comparing >50%, >30 - 50%, >15 - 30%, >5 - 15% probability vs ≤5% probability as the reference). To evaluate potential departures from linearity, we also evaluated flexible Loess lines using the 'geom_smooth' loess method in the R gglot2 package (Wickham, 2016).

2.6 Analyses stratified by EPA MCL time period, region, sociodemographic subgroups, CWS water source, and population served by public water systems

To determine if the association between private well arsenic and CWS arsenic changed over time, we stratified our analysis by the first two Final Arsenic Rule compliance monitoring periods (2006 - 2008 versus 2009 - 2011). We anticipated that the association between high probability wAs >10 μg/L and average CWS arsenic would be higher in the first monitoring period as CWSs may have reduced arsenic concentrations in the second period to ensure compliance with the 2006 MCL (via water treatment or switching/mixing source water) (United States Environmental Protection Agency, 2020a). We subtracted nationwide effect estimates for 2009 - 2011 from effect estimates for 2006 - 2008 to determine the mean difference in the association between the two time periods. To determine if changes in the association between high probability wAs >10 μg/L and CWS arsenic between 2006 - 2008 and 2009 - 2011 were consistent across the US, we repeated these analyses further stratifying by region, sociodemographic county-cluster, majority public water system source type, and the percent of population served by public water systems. These analyses enable us to evaluate whether certain subgroups of CWSs, identified by region, sociodemographic characteristics, and CWS water source, were likely applying treatment methods to reduce groundwater arsenic concentrations and meet MCL regulations. These findings can also elucidate subgroups of CWSs where further interventions to reduce groundwater arsenic exposures are needed. We visually evaluated potential differences in the linear association between high probability wAs > 10 μg/L and CWS arsenic concentrations for the entire time period (2006 - 2011) stratified by subgroup (region, sociodemographic county-cluster). Within region-specific analyses, we further stratified by majority public water system source type to determine if differences by region were explained by the type of source water most used by CWSs in a given region.

2.7 Sensitivity analyses

We conducted several sensitivity analyses to investigate internal consistency and to understand how different estimates of private well arsenic probability, developed in Lombard et al., would affect the observed association (Lombard, 2021b). First, we repeated our nationwide and stratified analyses using the mean probability wAs > 10 μg/L (rather than the 90th percentile) in order to evaluate how the association changed at the mean versus high end of the wAs > 10 μg/L distribution (Lombard, 2021b). Second, we evaluated the association between private well arsenic probability and average CWS arsenic using the 90th percentile of the probability of private well arsenic exceeding 5 and 1 μg/L (high probability wAs > 5 and 1 μg/L), rather than high probability wAs > 10 μg/L (Lombard, 2021b). These analyses

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evaluate drinking water arsenic MCLs for the states of New Jersey and New Hampshire (5 μg/L) and the Netherlands (1 μg/L) (Ahmad, 2020; National Research Council, 2001; New Hampshire Department of Environmental Services, 2018; New Jersey Department of Environmental Protection, 2020). Third, we conducted analyses that utilized county-level mean probability wAs > 10 μg/L that were generated from a random forest classification model (rather than from the boosted regression tree model) in order to evaluate how sensitive the findings are to model choice (Lombard, 2021b). The boosted regression tree models (high probability wAs > 10, 5 and 1 μg/L) were developed independently of each other and may not have consistent results between models at any given location (Lombard, 2021b). However, the random forest classification estimates were derived from a single model, supporting comparisons between the mean probability of groundwater arsenic < 5, > 5 to < 10, and > 10 μg/L at a given location or county as the sum of the probabilities across each of the categories equals 1 for each county (Lombard, 2021b). Finally, we repeated our analyses stratified by region after changing our region groupings to reflect those in the USGS Ground Water Atlas of the US (N=13 Ground Water Atlas region categories) (United States Geological Survey, 2016).

3. Results and Discussion

3.1 Nationwide descriptive results

A total of 2,231 counties (72% of all counties in the conterminous US) had data available for both the high probability wAs > 10 μg/L and average CWS arsenic concentrations from 2006 - 2011. Median CWS arsenic concentrations were higher in the Southwest (2.1 μg/L) and Central Midwest (1.4 μg/L) regions, as well as in *Rural, American Indian* (2.8 μg/L) and *Semi Urban, Hispanic* (2.3 μg/L) counties (Table 1). Overall, 53% of the counties evaluated (N= 1,178) had ≤5% high probability wAs > 10 μg/L, and only 3% (N= 59) of counties had high probability wAs >50% (Table 1). The percentage of counties with ≤5% of high probability wAs ranged from 8% in New England to 85% in the Southeast. County-level high probability wAs > 10 μg/L is generally elevated (>5% probability) in the Southwest and Pacific Northwest, and in parts of New England and the Central Midwest (Figure 1). These spatial patterns of private well water arsenic were conserved when estimated using boosted regression tree models and the mean probability wAs > 10 μg/L (Table S1, Figure 2).

3.2 Associations nationwide and by subgroup (2006-2011)

Nationwide, a one-unit increase (0 to 100%) in county-level 90th percentile probability of private well water arsenic (high probability wAs) > 10 μg/L was associated with an increase in county-level mean CWS arsenic concentration of 8.6 (95% confidence interval (CI) 7.8, 9.3) μg/L in 2006 - 2011 (Table 2). An alternative interpretation of this effect estimate is at the county level, mean CWS arsenic increased 0.86 μg/L per 10% increase in high probability wAs > 10μg/L. Figure 3 displays the association between high probability wAs > 10 μg/L and average CWS arsenic levels (μg/L) in 2006 - 2011 stratified by region and sociodemographic county cluster. In analyses stratified by region, the slope of the linear regression line between high probability wAs > 10 μg/L and CWS arsenic concentrations for 2006 - 2011 was steepest (i.e. the CWS arsenic concentration was highest at an equivalent high probability wAs > 10 μg/L) for the Central Midwest (17.5 μg/L, 95% CI 12.1, 22.8) and

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the Southwest (12.3 µg/L, 95% CI 10.2, 14.5) (Table S2). When analyses were stratified by county cluster, the slope was steepest for *Rural, American Indian* counties (22.0 µg/L, 95% CI 5.0, 38.9) and *Rural, Mid/Low SES* counties (22.0 µg/L, 95% CI 15.9, 28.2) (Table S2).

In analyses further stratifying region-specific comparisons by majority public water system source type, the strongest association between high probability wAs > 10 µg/L and CWS arsenic was observed in counties that source most (greater than 50%) of their drinking water from groundwater supplies in the Central Midwest (15.1 µg/L, 95% CI 9.3, 21.0), Southeast (9.8 µg/L, 95% CI 5.4, 14.2), and Southwest (12.8 µg/L, 95% CI 10.4, 15.3) (Figure 4, Table S3). In all regions except for New England, effect estimates were attenuated in counties that source the majority of their drinking water from surface water supplies, compared to those counties which source the majority of their drinking water from groundwater sources. For example, the effect estimate for the Central Midwest was 2.8 µg/L (95% CI −2.4, 8.0) for counties with majority surface water supplies compared to an effect estimate of 15.1 µg/L for counties in the same region that source greater than 50% from groundwater (Figure 4, Table S3). We found similar associations between high probability wAs and CWS arsenic by region and sociodemographic cluster using the high probability wAs exceeding 1 and 5 instead of 10 µg/L (Figures S1–S2).

In comparisons that categorized the high probability wAs > 10 µg/L (≤5, >5 - 15, >15 - 30, >30 - 50, >50%), the mean difference in CWS arsenic concentrations comparing counties with high probability wAs >50% versus counties with high probability wAs ≤5% (reference) was 5.8 µg/L (5.2, 6.4) nationwide (Figure 5, Table S4). The strongest associations between increasing high probability wAs > 10 µg/L and CWS arsenic concentrations were observed in the Southwest and Central Midwest, where mean CWS arsenic concentrations were 8.8 µg/L higher (7.2, 10.4) and 7.4 µg/L higher (2.2, 12.6), respectively, for counties with high probability wAs >50% versus counties with high probability wAs ≤5%. In the Southeast, Mid Atlantic, and New England regions, the association between high probability wAs > 10 µg/L and CWS arsenic was null across all categories of high probability wAs > 10 µg/L.

3.3 Differences over time (temporal changes from 2006 - 2008 to 2009 - 2011)

Nationwide, a unit (0 to 100%) change in the county-level high probability wAs > 10 µg/L was associated with mean county-level CWS arsenic concentrations of 8.4 µg/L (95% CI 7.7, 9.2) in 2006 - 2008 and of 7.3 µg/L (95% CI 6.6, 8.0) in 2009 - 2011 (Table 2). Between the two time periods, the association between high probability wAs > 10 µg/L and CWS arsenic concentrations decreased by 1.1 (95% CI 1.5, 0.7) µg/L. Figure 6 displays the nationwide results for the linear regression and flexible Loess models between high probability wAs > 10 µg/L and CWS arsenic concentration stratified by time period. In smooth Loess models, the association between high probability wAs > 10 µg/L and average CWS arsenic concentration (log-scale) was similar for both time periods at high probability less than 40%; above 40%, however, the association was attenuated in the second (2009 - 2011) compared to the first period (2006 - 2008) (Figure 6).

Table 2 also displays differences over time in the association between high probability wAs > 10 µg/L and CWS arsenic concentrations stratified by region, sociodemographic county cluster, and the percent of population served by public water systems. In 2006 - 2008, the

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increase in county-level mean CWS arsenic concentrations per 100% increase in high probability wAs > 10 µg/L were 16.5 µg/L (95% CI 11.0, 22.1) in the Central Midwest, 13.1 µg/L (95% CI 10.8, 15.3) in the Southwest, 5.3 µg/L (95% CI 3.4, 7.2) in the Pacific Northwest, 4.5 µg/L (95% CI 2.6, 6.4) in the Southeast, and 3.5 µg/L (95% CI 2.4, 4.5) in the Eastern Midwest. These estimates remained similar in 2009 - 2011. Between 2006 - 2008 and 2009 - 2011, the difference in these associations between the two time periods was largest in the Southwest (−2.1 µg/L, 95% CI −3.5, −0.8) and Southeast (−1.7 µg/L, 95% CI −3.1, −0.3) (Table 2). By sociodemographic county cluster, the difference in the association between high probability wAs > 10 µg/L and CWS arsenic concentrations from 2006 - 2008 to 2009 - 2011 was −12.5 µg/L (95% CI −17.7, −7.2) in *Rural, Mid/Low SES* counties; −2.4 µg/L (95% CI −3.1, −1.8) in *Mostly Rural, Mid SES* counties; and −1.2 µg/L (95% CI −2.1, −0.3) in *Rural, High SES* counties (Table 2). No significant differences in the association over time were observed for other sociodemographic county clusters. In analyses stratified by the percent of the population served by public water systems, the association between high probability wAs > 10 µg/L and CWS arsenic concentrations for counties with 10 - 30% of the population served by public water systems was 14.0 µg/L (95% CI 10.2, 17.8) in 2006 - 2008 and 12.5 µg/L (95% CI 9.6, 15.3) in 2009 - 2011. Table S3 presents differences in the association between high probability wAs > 10 µg/L and CWS arsenic over time stratified by both region and majority water supply (groundwater versus surface water). From 2006 - 2008 to 2009 - 2011, the largest and significant declines in the association between high probability wAs > 10 µg/L and CWS arsenic occurred in counties with majority groundwater supplies nationwide (−1.5 µg/L, 95% CI −2.0, −0.9) and in the Southwest (−3.1 µg/L, 95% CI −4.7, −1.) (Table S3).

3.4 Sensitivity analyses results

Sensitivity analyses comparing the mean difference in CWS arsenic concentration per unit (0 to 100%) change in high probability wAs > 5 and 1 µg/L found similar patterns regionally as those using the high probability wAs > 10 µg/L; however, the nationwide effect estimates were attenuated in models evaluating high probability wAs > 5 and 1 µg/L (Table S5, Figure S3). Results from linear analyses stratified by sociodemographic county cluster were not consistent across models evaluating the high probability wAs > 10, 5 and 1 µg/L, although *Rural, Mid/Low SES* counties had a large and significant decline in the association across all models for high probability wAs (Table S6). This finding aligns with our expectation that the association between private well arsenic and CWS arsenic would decline over time for counties that approached and/or exceeded the 10 µg/L MCL from 2006-2008, and where CWSs and private wells are supplied by similar groundwater sources. Using different regional classifications of states based on the USGS Hydrologic Atlas pointed to similar results in linear regression analyses stratified by region (Table S7)(United States Geological Survey, 2016). Additional sensitivity analyses using the mean probability wAs > 10, 5 and 1 µg/L yielded similar results as those using the 90th percentile probability (Figures S4–S5). Further, effect estimates using mean probability wAs > 10, 5 and 1 µg/L derived from random forest models were similar to our main findings (results not shown).

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3.5 Regional differences in improved water resources

The findings of this nationwide study combining private well arsenic data and CWS arsenic data support the hypotheses that private well water arsenic is associated with CWS arsenic concentrations nationwide and that these associations differ both spatially and temporally (Lombard, 2021b; Nigra, 2020b). County-level high probability wAs > 10 µg/L was positively and significantly associated with county-level CWS arsenic concentrations from 2006 - 2011, but associations were strongest in the Central Midwest, Eastern Midwest, Pacific Northwest, and Southwest regions, and null in the Mid-Atlantic and New England regions. Nationwide, the association between private well arsenic and CWS arsenic concentrations was attenuated in the second compliance monitoring period (2009 - 2011), especially for counties with high probability wAs above 40%, which likely reflects that CWSs implemented treatment systems or switched source water in accordance with the Final Arsenic Rule MCL change.

The change in the association between high probability wAs > 10 µg/L and CWS arsenic levels over time, quantified as the mean change in slopes between the monitoring periods, also varied regionally. These findings suggest that interventions to implement the new Final Arsenic Rule MCL (10 µg/L) were more pronounced in some regions. For instance, the strongest decline over the two periods was observed in the Southwest, a region known to have high concentrations of geogenic arsenic in groundwater (Ayotte, 2017). In the Southwest, a strong association between private well and CWS water arsenic persisted in the second period despite the large and significant decline. However, no significant decline was observed for counties in the Central Midwest, the region with the strongest association between private well arsenic and CWS arsenic concentrations during both monitoring periods. These findings are consistent with prior work which evaluated changes in CWS arsenic concentrations associated with the Final Arsenic Rule MCL change, which found that the CWS arsenic concentrations in the Southwest and the Central Midwest remained relatively high even after implementation of the Final Arsenic Rule (Nigra, 2020b).

3.6 Socioeconomic inequities in availability of improved water resources

In analyses stratified by sociodemographic group, the largest associations between private well arsenic and CWS arsenic concentrations were observed in *Rural, American Indian* and *Rural, Mid/Low SES* counties during both monitoring periods. However, *Rural, American Indian*, and *Rural, Mid/Low SES* counties also experienced the greatest decline in the observed association from 2006 - 2008 to 2009 - 2011. These findings may reflect the impact of federal funding programs in rural communities (e.g., US Department of Agriculture and Indian Health Service) which fund public water system infrastructure to reduce public water system arsenic concentrations in accordance with the 2006 arsenic MCL. Conversely, the strength of the association between private well arsenic and CWS arsenic increased over time from 2006 - 2008 to 2009 - 2011 in *Semi Urban, Hispanic* counties (Table 2). The variability in the association between counties within a given classification may indicate that individual community responses to changing conditions vary in approach and efficacy. Given these findings, and prior findings of elevated CWS arsenic exposure in these counties, future research, regulatory attention, and support are needed to

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understand and mitigate ongoing challenges to reducing water arsenic exposure in these communities.

Our findings suggest that arsenic concentrations in groundwater-dependent CWSs and in private wells are similar in most US regions. These findings also indicate that private well water arsenic may not represent a good surrogate for groundwater arsenic in regions where aquifers used for private wells and CWSs differ, or where CWSs depend largely on surface water supplies. For instance, some CWSs in New England use shallower aquifers than those represented by private well water estimates(United States Environmental Protection Agency, 2017a). Also, in the Mid-Atlantic and New England, most large CWS freshwater withdrawals are from surface water supplies (Table S8), which may explain the lack of a linear association between private well and CWS arsenic in these regions (Maupin, 2014; United States Geological Survey, 2010). MCL implementation may have little effect on the association between private well arsenic and CWS arsenic in these regions because surface water typically has low arsenic concentrations compared to groundwater. These results also highlight that users of private wells, which are not covered by federal CWS drinking water regulation and compliance monitoring, remain susceptible to elevated drinking water arsenic exposure. Two complementary analyses support that water arsenic exposure declined after the 2006 MCL change for CWS users, but not for private wells (Nigra, 2017; Welch, 2018). Testing of arsenic and other contaminants in private wells is infrequently conducted and treatment systems in individual households can often be poorly maintained due to a variety of factors, including cost; significant socioeconomic disparities in private well arsenic testing and treatment exist in the US (Flanagan, 2016; Malecki, 2017; Yang, 2020). Additional efforts are needed to support private well users in testing, treating, and maintaining treatment removal systems for arsenic, especially those residing in areas with elevated groundwater arsenic concentrations (Flanagan, 2016). Our research supports that the bidirectionality of the association between private well and CWS arsenic can help guide private well interventions to prevent arsenic exposure by leveraging CWS arsenic information. Linear models of the reversed association, between CWS arsenic (independent variable) and private well arsenic (dependent variable), found a similar positive association nationwide (not shown), and by region and sociodemographic county cluster (Figure S6). Further research can further evaluate how CWS data can be leveraged to inform on the probability of private well arsenic as the primary outcome.

3.7 Limitations and Future Uses

One potential limitation of the current study is the uncertainty in the probability estimates for private well water arsenic. This source of measurement error, however, would likely be non-differential and thus bias the associations towards the null. Our results were consistent across sensitivity analyses using boosted regression tree models to estimate high probability wAs > 1 and 5 µg/L, and for sensitivity analyses using the mean probability wAs >10, 5, and 1 µg/L rather than the 90th percentile, indicating that our results were robust across several different approaches to modeling private well arsenic. Results were also similar when grouping states into regions based on USGS Hydrologic Atlas regions (United States Geological Survey, 2016). Another limitation of this study involves the assumption that private well arsenic is stable over time; a survey of arsenic concentrations in drinking water

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supplies in the US found that arsenic concentrations in private wells have generally low temporal variability within each well over time scales ranging from less than a year to over a decade (Ayotte, 2015). However, recent and growing evidence indicates that timing since well construction, excessive well pumping and ground subsidence, and drought may impact arsenic concentrations in groundwater (Erban, 2013; Erickson, 2018; Lombard, 2021c; Smith, 2018). An additional limitation of this study includes the lack of CWS arsenic exposure estimate data from several states (CO, DE, GA, MD, MS). However, our analysis included approximately 72% of all counties in the conterminous US. We were unable to evaluate the association between private well arsenic and CWS arsenic concentrations at a smaller geographic resolution than county (e.g. zip code or census block), because CWS arsenic exposure estimates are not yet available at these resolutions. These estimates were derived from compliance monitoring data in the EPA SYR database by linking compliance monitoring data for CWSs to the county/counties served by each CWS, as reported by EPA in the Safe Drinking Water Information System (United States Environmental Protection Agency, 2020c). Future analyses would greatly benefit from arsenic exposure estimates developed across the entire US at a finer geographic resolution.

3.8 Conclusions

These findings pose important implications for EPA MCL regulation for arsenic in public drinking water, as well as for assessing unregulated arsenic in private well water. They highlight the need for future research in groundwater science and help target the need for further interventions to assist public water systems in attaining compliance with the arsenic MCL, particularly in the Southwestern and Central Midwestern US and in *Rural, American Indian; Semi Urban, Hispanic; and Rural, Mid/Low SES* communities. These findings may be used in future research to elucidate regions and communities where large disparities in arsenic exposure between CWS and private well users persist. These findings can be used in future human health studies assessing drinking water arsenic exposure and health outcomes, such as diabetes or cardiovascular disease.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- We compared arsenic exposure from private wells and community water systems (CWSs).
- County-level private well and CWS arsenic were positively associated nationwide.
- Association differed by region, CWS water source, and sociodemographic attributes.
- Association declined nationwide over time, after Final Arsenic Rule implementation.

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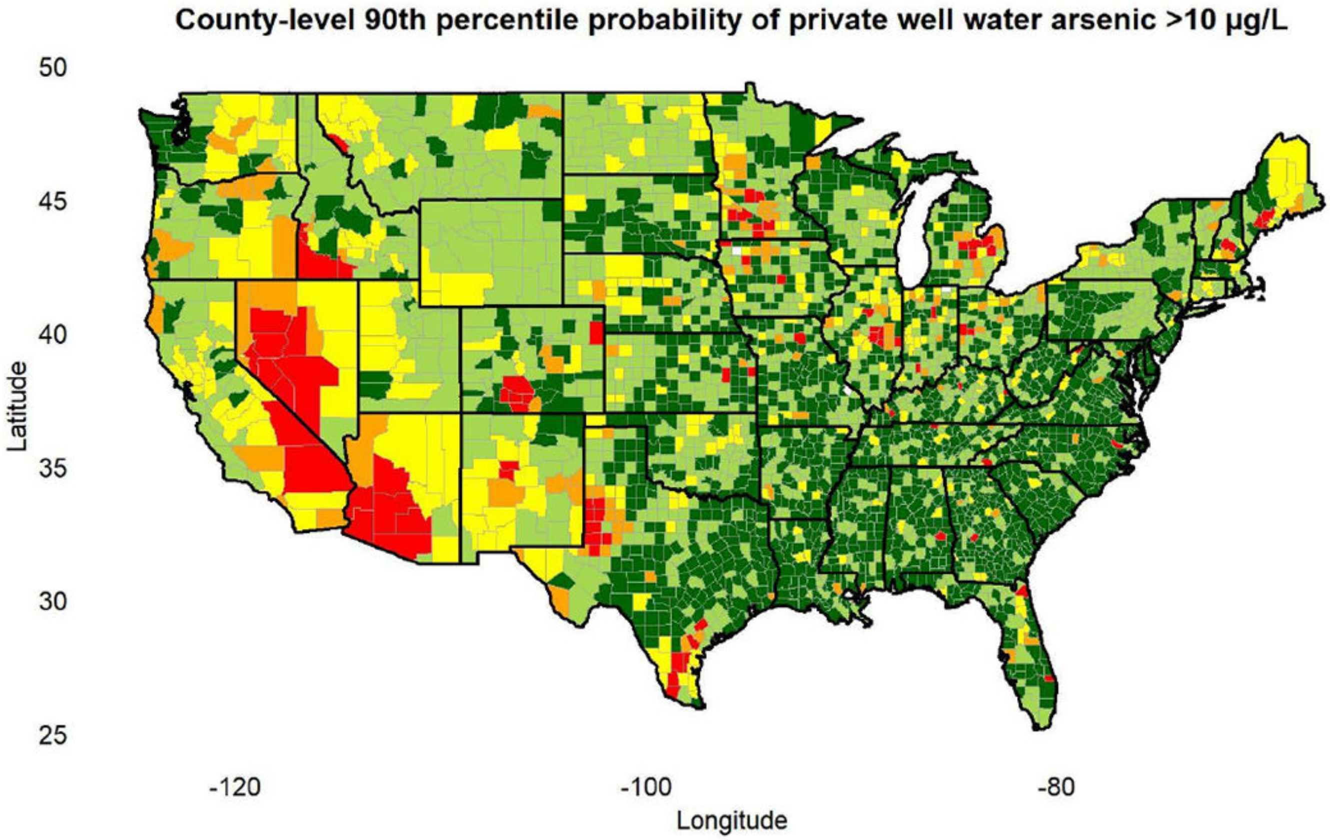

Figure 1. County-level high probability private well water arsenic (wAs) > 10 µg/L across the conterminous US (N=3,109 counties)[1].

NA = Not available.

[1] Map data attributable to Lombard 2021a, © OpenStreetMap contributors.

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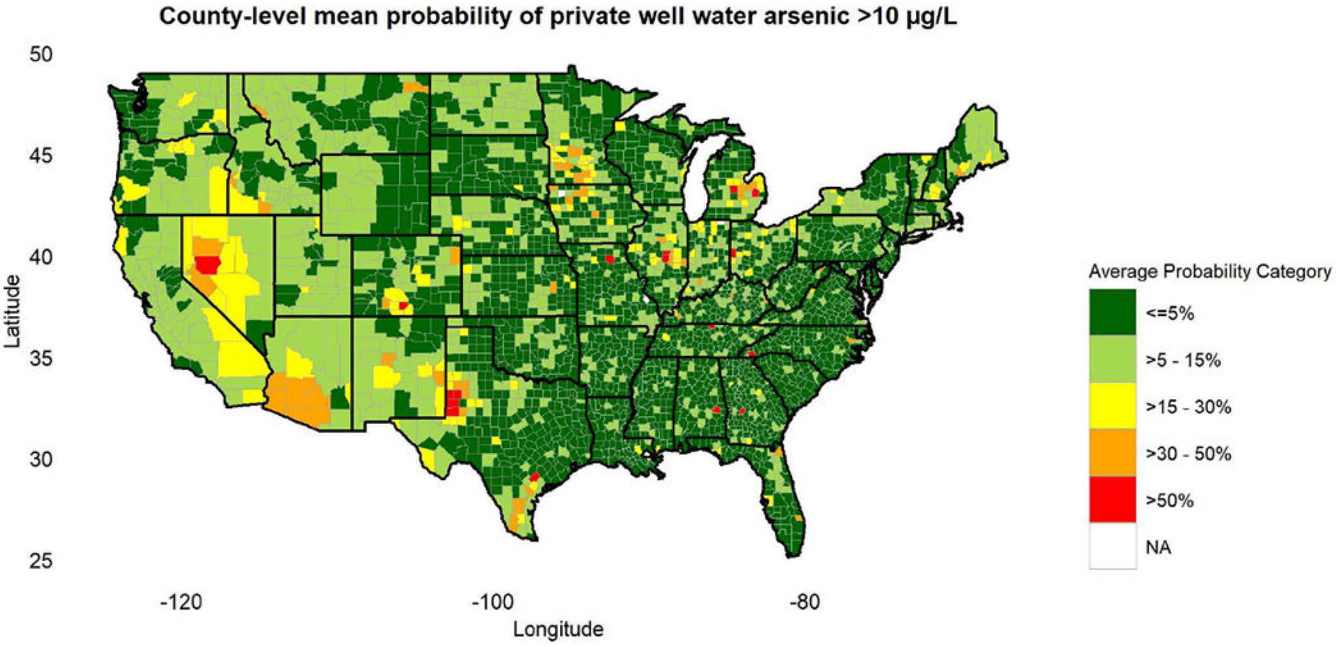

Figure 2. County-level mean probability private well water arsenic (wAs) > 10 µg/L across the conterminous US[1]

NA = Not available.

[1] Map data attributable to Lombard 2021a, © OpenStreetMap contributors.

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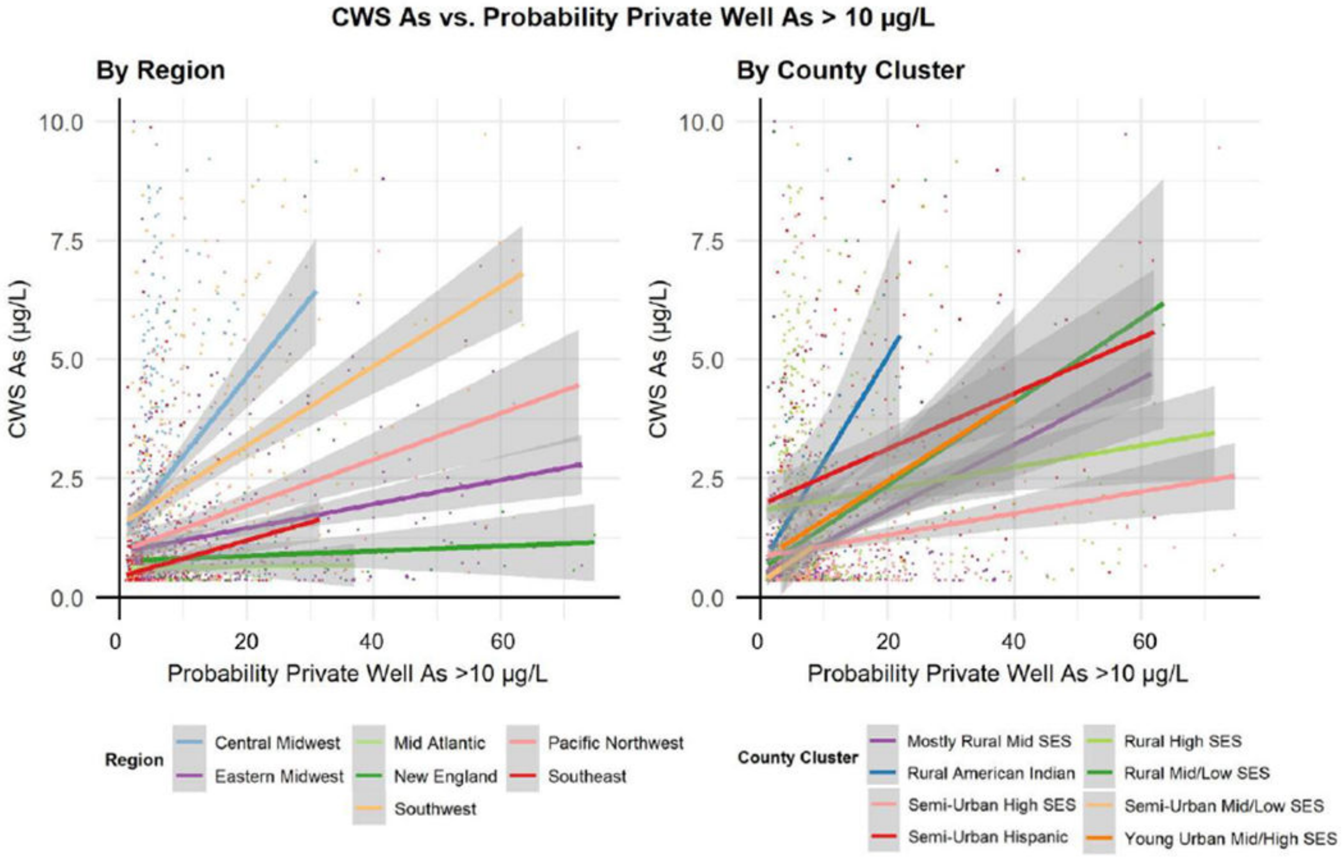

Figure 3. County-level community water system (CWS) arsenic (µg/L) in 2006-2011 by high probability private well water arsenic (wAs) > 10 µg/L across the conterminous US, by region and sociodemographic county cluster.

Dots represent counties. Lines represent the relationship between private well and CWS arsenic based on linear regression models. Shades represent 95% confidence intervals.

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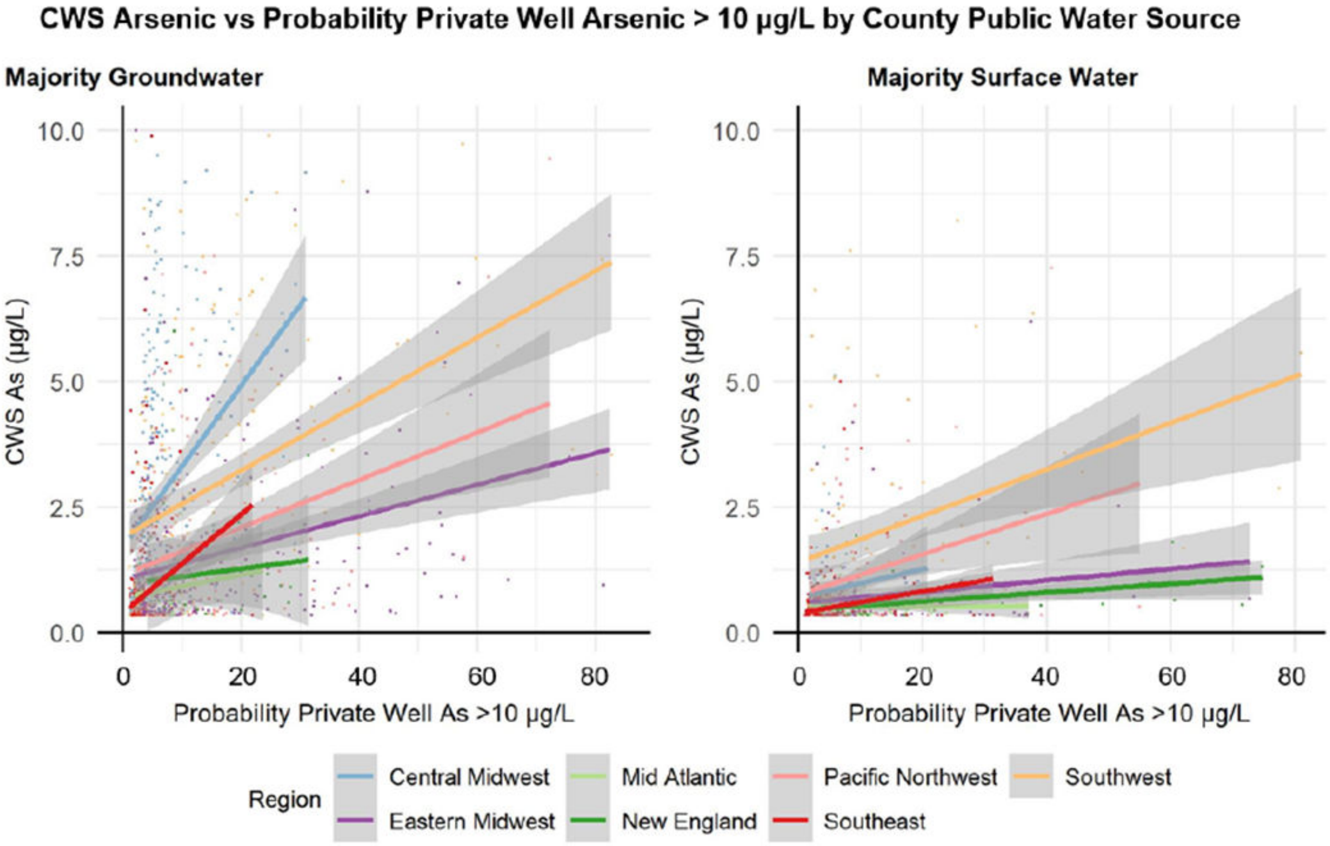

Figure 4. County-level community water system (CWS) arsenic concentrations (μg/L) in 2006-2011 by high probability private well water arsenic (wAs) > 10 μg/L across the conterminous US, by majority water source.

Dots represent counties. Lines represent the relationship between private well and CWS arsenic based on linear regression models. Shades represent 95% confidence intervals.

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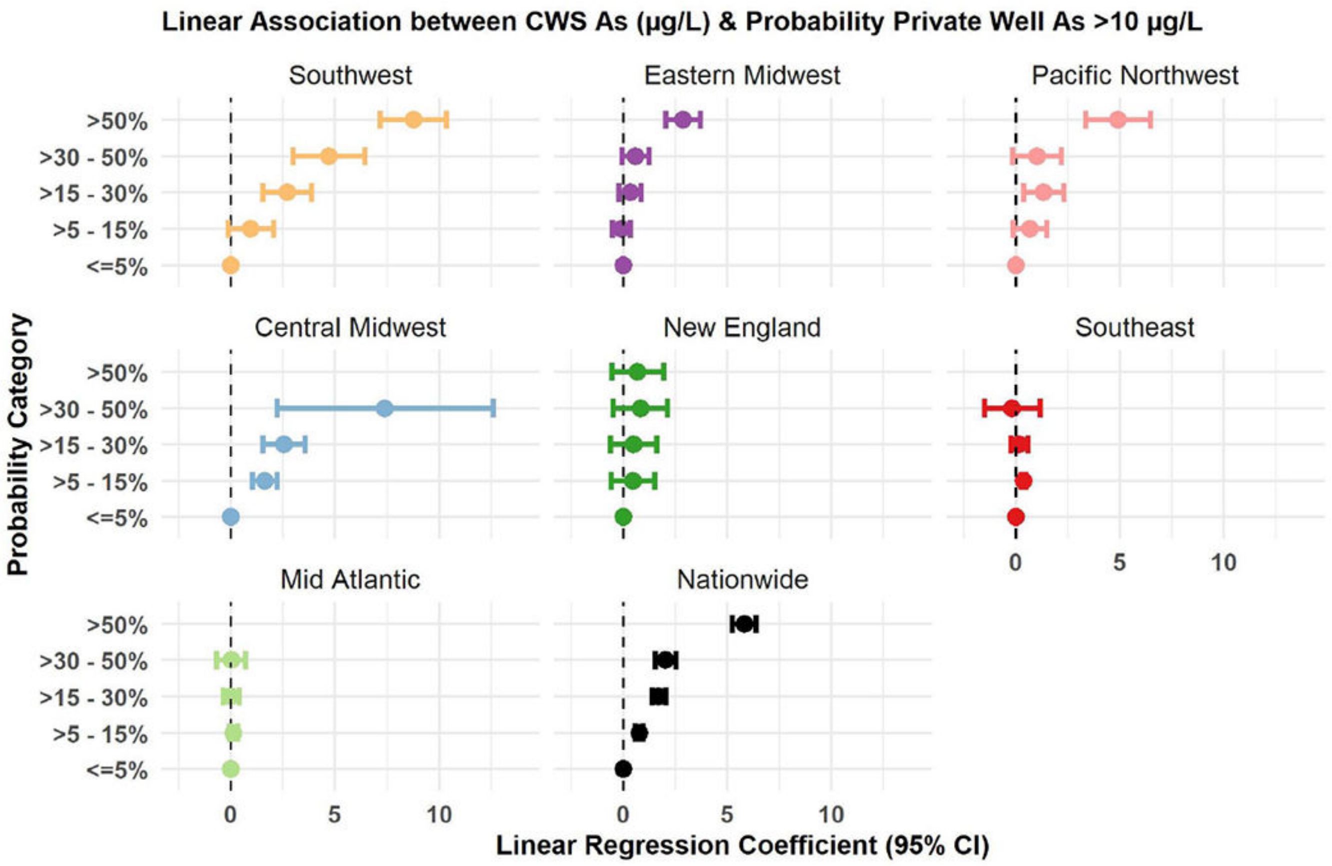

Figure 5.

Linear associations (95% confidence interval (CI)) between high probability private well water arsenic (wAs) > 10 µg/L and community water system (CWS) arsenic concentrations comparing counties with high probability wAs >5-15%, >15-30%, >30-50%, and >50%, versus counties with high probability wAs ≤5% (reference), 2006-2011.

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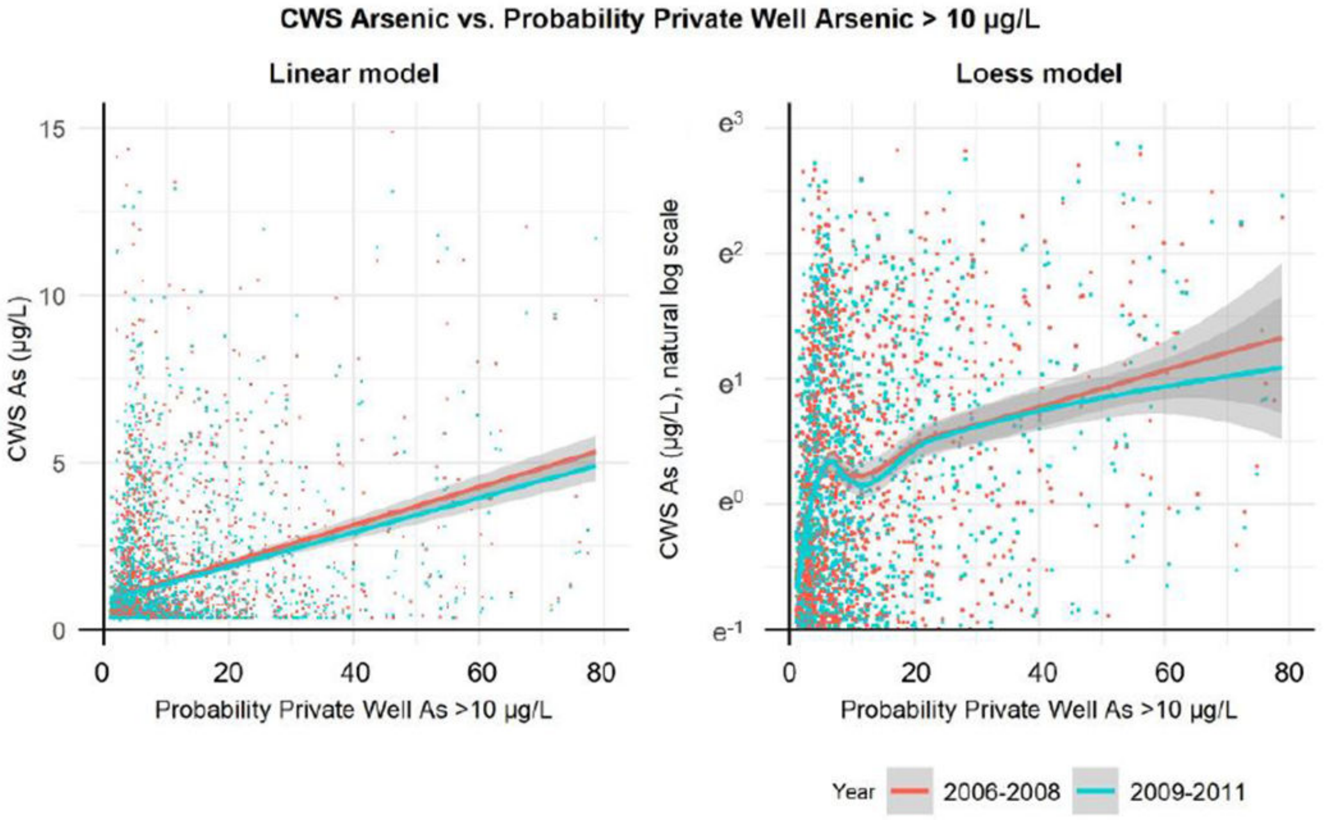

Figure 6. County-level community water system (CWS) arsenic (μg/L) in 2006-2008, 2009-2011 by high probability private well water arsenic (wAs) > 10 μg/L across the conterminous US on the original scale using a linear regression model (left), and on the natural log scale using a Loess model (right). Dots represent counties. Lines represent the relationship between private well and CWS arsenic based on linear (left) and loess (right) models. Shades represent 95% confidence intervals.

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Table 1.

Quantile of county-level community water system (CWS) arsenic concentrations (μg/L) and high probability[a] of private well water arsenic (wAs) >10 μg/L by county characteristics (N = 2231), (2006-2011). SES = socioeconomic status.

	N	CWS arsenic (μg/L)	High probability (%) private well arsenic >10 μg/L					
			Continuous probability	≤5	>15–30	>30–50	>50	
		50% (75% 95%)	50% (75% 95%)	% Counties by row				
Nationwide, 2006–2011	2231	0.6 (1.5, 6.0)	5 (10, 35)	53	31	10	4	3
Region[b]								
Central Midwest	351	1.4 (4.0, 8.2)	5 (7, 18)	55	36	9	–	–
Eastern Midwest	395	0.7 (1.6, 4.7)	9 (19, 51)	32	37	16	10	5
Mid-Atlantic	160	0.4 (0.6, 1.6)	7 (10,21)	35	56	8	2	–
New England	53	0.6 (0.9, 2.3)	13 (28, 60)	8	45	26	9	11
Pacific Northwest	189	0.9 (2.2, 5.2)	10 (15, 39)	11	63	16	7	3
Southeast	795	0.4 (0.5, 1.2)	3 (4, 8)	85	14	1	0	–
Southwest	288	2.1 (4.5, 11)	9 (22, 62)	36	27	21	7	9
Sociodemographic cluster[c]								
Mostly Rural, Mid SES	742	0.4 (0.7, 3.8)	3 (6, 25)	67	23	6	2	1
Rural, American Indian	21	2.8 (4.2, 6.3)	9 (13, 19)	24	62	14	–	–
Rural, Mid/Low SES	80	0.4 (0.7, 5.8)	3 (4, 26)	78	15	5	–	3
Rural, High SES	484	1.2 (3.2, 7.1)	6 (12, 41)	38	42	12	5	4
Semi Urban, Hispanic	158	2.3 (5.1, 11)	10 (24, 63)	28	30	20	11	11
Semi Urban, Mid/Low SES	158	0.4 (0.4, 1.3)	2 (3, 6)	91	9	–	–	–
Semi Urban, High SES	553	0.6 (1.1, 4.5)	7 (12, 32)	40	40	13	4	2
Young Urban Mid/High SES	24	1.7 (2.4, 4.4)	10 (20, 26)	29	29	38	4	–
% served by CWS[d]								
≤10%	8	0.4 (0.7, 1.8)	2 (3, 14)	88	–	13	–	–
>10 to 30%	102	0.8 (2.4, 6.8)	4 (8, 32)	63	24	8	3	3
>30 to 50%	284	0.5 (0.9, 5.1)	4 (10, 37)	54	32	8	5	2
>50%	1832	0.6 (1.6, 6.0)	5 (10, 34)	52	31	10	3	3

[a] 90th percentile probability of private well water arsenic.

[b] Region groupings: Central Midwest (ND, SD, NE, KS, MO), Eastern Midwest (WI, IL, IN, MI, OH, MN, IA), Mid-Atlantic (PA, MD, DC, DE, NY, NJ, CT, RI), New England (MA, VT, NH, ME), Pacific Northwest (WA, OR, MT, WY, and ID), Southeast (OK, AR, LA, MS, AL, FL, GA, TN, KY, SC, NC, VA, WV), Southwest (CA, NV, UT, CO, AZ, NM, TX).

[c] Wallace et al. (2019).

[d] Maupin et al. (2014). 2010 water use estimates used to determine percent of county population served by public water systems.

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Table 2.

Associated change in average community water system (CWS) arsenic concentration (μ/L) per 100% increase in high probability private well water arsenic (wAs) > 10 μg/L overall and stratified by time period (2006-2008 versus 2009-2011), region, sociodemographic county cluster, and percent of population served by public water supplies.

SES = socioeconomic status. CI = confidence interval.

		Estimate (95% CI)		
	N	**2006-2011**		
Nationwide	**2,231**	**8.6 (7.8, 9.3)**		
	N	**2006-2008**	**2009-2011**	**Difference**[3]
Nationwide	2,231	8.4 (7.7, 9.2)	7.3 (6.6, 7.9)	−1.1 (−1.5, −0.7)
Region				
Central Midwest	351	17 (11, 22)	17 (12, 22)	0.5 (−2.0, 3.0)
Eastern Midwest	395	3.5 (2.4, 4.5)	3.3 (2.3, 4.3)	−0.2 (−1.1, 0.7)
Mid-Atlantic	160	0.2 (−1.2, 1.6)	0.0 (−1.4, 1.3)	−0.2 (−1.0, 0.6)
New England	53	0.9 (−0.8, 2.7)	0.5 (−0.3, 1.3)	−0.4 (−1.6, 0.7)
Pacific Northwest	189	5.3 (3.4, 7.2)	5.7 (3.8, 7.6)	0.4 (−0.6, 1.3)
Southeast	795	4.5 (2.6, 6.4)	2.8 (1.4, 4.3)	−1.7 (−3.1, −0.3)
Southwest	288	13 (11, 15)	11 (9.0, 13)	−2.1 (−3.5, −0.8)
Sociodemographic county cluster[1]				
Mostly Rural, Mid SES	742	9.3 (8.3, 10)	6.9 (6.1, 7.6)	−2.4 (−3.1, −1.8)
Rural, American Indian	21	28 (8.8, 47)	16 (−0.9, 33)	−12 (−31, 6.5)
Rural, Mid/Low SES	80	27 (20, 35)	15 (10, 19)	−12 (−18, −7.2)
Rural, High SES	484	3.1 (1.3, 4.9)	1.9 (0.3, 3.6)	−1.2 (−2.1, −0.3)
Semi Urban, Hispanic	158	11 (8.0, 14)	11 (8.1, 14)	0.3 (−1.1, 1.6)
Semi Urban, Mid/Low SES	158	13 (−4.8, 31)	2.9 (−7.5, 13)	−10 (−22., 2.0)
Semi Urban, High SES	553	4.3 (3.1, 5.6)	3.9 (2.8, 5.0)	−0.4 (−1.1, 0.2)
Young Urban Mid/High SES	24	8.4 (1.2, 16)	11 (1.3, 21)	2.5 (−1.9, 6.9)
Population served by CWS[2] **(%)**				
< 10	8	−0.5 (−11.8, 10.8)	−0.7 (−4.2, 2.9)	−0.2 (−9.0, 8.6)
10 to 30	102	14.0 (10.2, 17.8)	12.5 (9.6, 15.3)	−1.6 (−4.5, 1.3)
30 to 50	284	6.3 (4.9, 7.6)	5.5 (4.1, 7.0)	−0.7 (−1.7, 0.3)
> 50	1832	8.4 (7.6, 9.3)	7.3 (6.5, 8.0)	−1.2 (−1.6, −0.7)

[1] Wallace et al. (2019).

[2] Maupin et al. (2014). 2010 water use estimates used to determine percent of county population served by CWSs.

[3] The “Difference” column presents the difference in the association between time periods (mean change in linear regression slope between time periods).

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