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Arsenic Drinking Water Violations Decreased Across the United States Following Revision of the Maximum Contaminant Level

Stephanie A. Foster[1], **Michael J. Pennino**[2], **Jana E. Compton**[3], **Scott G. Leibowitz**[3], **Molly L. Kile**[1]

[1]College of Public Health and Human Sciences, Oregon State University, Corvallis, Oregon 97331, United States

[2]US EPA, Office of Research and Development, National Center for Environmental Assessment, Washington, DC 20460, United States

[3]US Environmental Protection Agency, National Health and Environmental Effects Research Laboratory, Western Ecology Division, Corvallis, Oregon 97333, United States

Abstract

Arsenic poses a threat to public health due to widespread environmental prevalence and known carcinogenic effects. In 2001, the US EPA published the Final Arsenic Rule (FAR) for public drinking water, reducing the maximum contaminant level (MCL) from 50 μg/L to 10 μg/L. We investigated impacts of the FAR on drinking water violations temporally and geographically using the Safe Drinking Water Information System. Violations exceeding the MCL and the population served by violating systems were analyzed across the conterminous US from 2006 (onset of FAR enforcement) to 2017. The percentage of public water system violations declined from 1.3% in 2008 to 0.55% in 2017 ($p < 0.001$, slope= −0.070), and the population served decreased by over 1 million ($p<0.001$, slope = −106,886). Geographical analysis demonstrated higher mean violations and populations served were concentrated in certain counties rather than evenly distributed across states. The decline in violations is likely due to adoption of documented and undocumented treatment methods, and possibly from reduced environmental releases. Considering other studies have shown decreased urinary arsenic levels in the population served by public water systems since the new standard, it may be inferred that the FAR is facilitating reduction of arsenic exposure in the US

Graphical Abstract

*Corresponding author fosters2@oregonstate.edu.

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INTRODUCTION

Inorganic arsenic (As), a Group 1 human carcinogen, can be elevated in drinking water where it poses a threat to public health. Chronic ingestion of As increases the risk of cancer in the lung, bladder, liver, kidney, and skin,[1–8] as well as ischemic heart disease, atherosclerosis, peripheral neuropathy, diabetes, and skin lesions.[9–12] The United States (US) has enacted regulations to control As releases, yet there remain many anthropogenic and natural sources of As in the environment.[7,13] For example, As is commonly found in hazardous waste sites.[14] It was also previously used to manufacture pharmaceuticals, pesticides and biocides, wood preservatives, and livestock feed additives.[7,15] While these industrial practices have stopped, they have contributed to As contamination of soil, waste streams, and water.[16–18] Arsenic is still used in glass manufacturing and semi-conductor industries[7] and can be released from mining activities.[19] These sources and others contribute to contemporaneous emissions that are captured by the US Environmental Protection Agency's (EPA) Toxics Release Inventory (TRI) and may contribute to environmental contamination.[20,21] Arsenic also occurs naturally in certain geologic formations and soil types where it can be released into the atmosphere from erosion, volcanic activity, and forest fires.[15,22] Under certain hydrological conditions, As can be mobilized out of bedrock and contaminate groundwater aquifers.[23–28] There are several regions in the US known to have naturally high levels of As, including the West, Southwest, Great Lakes Region, and Northeast.[7,24,29] However, As-contaminated groundwater aquifers and surface waters are found across the US

To reduce human exposure, the US has federally regulated arsenic as a drinking water contaminant since 1942. The original standard was promulgated for interstate water carriers by the Public Health Service and set at 50 μg/L.[30] In 1974, the Safe Drinking Water Act (SDWA) was enacted, and the prior As standard was incorporated as the maximum contaminant level (MCL) into the National Interim Primary Drinking Water Regulations.[30] In January of 2001 the EPA finalized a new rule for As in drinking water that lowered the MCL to 10 μg/L.[30] This revision, known as the Final Arsenic Rule (FAR), was based on a cost-benefit analysis comparing the costs of removing As from drinking water with the estimated costs of bladder and lung cancer attributed to As exposures from drinking water.[31]

The new regulation, which also mandated improved analytical detection and monitoring methods, became enforceable on January 23, 2006.[30,32] As anticipated, this change in regulation was associated with a spike in the number of municipal water systems in violation of the FAR MCL between 2004 and 2011, thereby revealing the number of systems that had elevated As levels but were below the previous MCL.[33] A study involving two different EPA databases estimated that 5–10 million people could have been served by a non-compliant municipal water system since enforcement of the FAR.[34] Also, non-compliant municipal water systems were more likely to be located in the southwestern US and to be serving smaller populations and communities with lower median household incomes.[33,34]

Biomonitoring data collected by the National Health and Nutrition Examination Survey, a representative sample of the non-institutionalized US population, reported a significant decrease in urinary As levels between 2003 and 2014.[35,36] Interestingly, the decrease in urinary As levels was found only among people who reported using public water systems (PWS), not among people who reported using private wells, bottled water, or other non-regulated water systems. Our study builds upon these reports by examining temporal and geographical FAR violation trends for PWS within the conterminous US (CONUS) from 2006 to 2017 using EPA's Safe Drinking Water Information System (SDWIS).[37] This database is publicly available and includes all reported health-based violations for regulated PWS in the US. Additionally, we estimated the population served by violating systems and examined the relationship between violation occurrence and water source, system size, and geographical location, as well as the duration of system violations. Finally, we investigated water treatment and anthropogenic releases as implicated drivers in the reduction of violations

MATERIALS AND METHODS

Background and Data Sources

PWS supply most (>86%) of the US population's drinking water.[38,39] By definition, PWS regularly serve drinking water to at least 15 service connections or an average of at least 25 people daily for a minimum of 60 days per year.[38] Individuals not serviced by PWS often receive their water supply from a non-regulated source, such as a domestic well.[39] Private wells can be regulated by state and local governments, but they are not federally regulated. Over 151,000 PWS are active in the US, and they can be sourced from surface water (SW), groundwater (GW), or a combination of the two.[38,40] GW is the source for most PWS in the US, but a much larger percentage of the population relies on SW-sourced systems.[40]

PWS can be further categorized by system type. Community water systems (CWS) supply water to the same people year-round.[40] Most residences in cities, small towns, or mobile home parks receive their water from CWS.[41] Non-transient non-community water systems (NTNCWS) regularly serve water to at least 15 service connections or an average of at least 25 of the same people over at least 6 months of the year.[40] For example, schools, office buildings, and hospitals are often serviced by NTNCWS. Finally, transient non-community water systems (TNCWS) serve water to people who do not stay in the area for long periods of time, such as at campgrounds or gas stations. TNCWS do not regularly serve water to at least 25 of the same persons over 6 months of the year.[40] Any PWS can host one or more facilities distributing drinking water to the public, such as a cistern, intake, pump, spring, storage, treatment plant, or well.[42]

Since 1974, PWS have been regulated under SDWA.[41] Systems must monitor for a variety of contaminants, including but not limited to coliforms, disinfection byproducts, organic contaminants (e.g., benzene and atrazine), inorganic contaminants (e.g., As, nitrate/nitrite, lead, copper), and radionuclides.[40] Under the current As regulation, systems are required to sample annually if they are SW and triennially if they are GW.[32] If a system has results above the MCL, then monitoring is increased to a quarterly basis until they again become eligible for reduced monitoring. Eligibility for a return to reduced monitoring is determined by the state but must involve the PWS consistently demonstrating levels below the MCL (at least two quarters for GW and at least four quarters for SW).[32] PWS must report As sampling results to the state, which then reports violations to the EPA for entry into SDWIS.[32] Only CWS and NTNCWS are subject to the FAR, so we confined our analysis to these two system types

Analysis of Data

Arsenic violations data across the CONUS were retrieved from the SDWIS database.[32] Using the SDWIS Federal Reports Advanced Search tool[37] under the "Violations" report option, we selected the Average and Single Sample Maximum Contaminant Level Violation; the Violation Rule was set to "Arsenic"; and the Activity Status was set to "All." All other filters were left at the default. Information on water source, system type, state and county, and year and quarter of the violation (based on the compliance period begin date) were acquired. PWS inventory data (number of systems active for at least part of the associated fiscal year) and yearly estimates for the total population served were provided by EPA's Office of Ground Water and Drinking Water.

To understand baseline trends prior to FAR enactment in 2001, an initial analysis included all inventoried violations from 1976 to 2017. However, subsequent analyses focused on the years 2006 to 2017, which had the same reporting conditions and allowed us to evaluate trends since the FAR became enforceable. Computed metrics are given in Table S1, which include the number and percent of systems in violation per calendar year, the number and percent of people served by systems in violation, the maximum violation duration for systems in years, and other metrics regarding system characteristics. Pennino et al. describes how violations and population served were estimated.[42] Linear regression was utilized to test for trends over time. In cases where model residuals and density plot tests did not exhibit normality or homogeneity, the Mann-Kendall test was applied to test the significance of temporal trends and the Sen's slope method was incorporated to estimate linear regression slope coefficients. An alpha threshold of 0.05 was used for significance tests. State and county information for each violating PWS was incorporated for analysis of geographical trends across the CONUS using ArcGIS.[43] Analysis was performed using R statistical software.[44]

To calculate percentages, we included the total number of systems and population served by PWS into the respective denominator for each year. System size classes were not reported in SDWIS but were categorized based on the population served, so no totals were available to calculate percentage violation values by system size. Also, system inventory totals were not available at the county level. When calculating the percent of the population served by violating systems, only CWS inventory data was included to prevent any potential overlap between CWS and NTNCWS use by individuals. Only one violation per PWS was used each year to determine the number of systems in violation. Additionally, note that the population served is not the same as the population affected by a drinking water violation or exposed to As. For example, there may be only one facility out of several within a certain PWS triggering a FAR violation. Therefore, populations served by the other facilities may not be at risk of As exposure, but SDWIS does not track the population served at the facility level.

We sought to better understand what may have caused observed reductions in As violations over time by examining two factors: lowering As input to the environment and using As-specific treatment. We explored EPA's TRI to determine trends in As release, which had the potential to affect FAR violation occurrence in the absence of treatment.[45] US facilities in certain industry sectors are required to report annually how much As they emitted or placed in land disposal. Our TRI analysis examined trends in releases of As over time from 2006–2017 in the CONUS and quantified the rate of change from 2013–2017. To explore the role of treatment on trends in violations, we first researched treatments included within SDWIS that are considered effective for As removal[7,9] (Table S2). Second, we obtained treatment information from SDWIS for all violating systems between 2013 to 2017. Systems with no documented As-specific treatment were considered as having no treatment. The percent change per year in the number of systems and the percent of systems violating was calculated and stratified by treatment and no treatment groups. The number of active systems for each year was used as the denominator for each group when calculating the percent of systems violating. Treatment information was not available for calculating percentages prior to 2013. Arsenic removal technologies have improved since initiation of the FAR,[46] and some of these newer technologies, often utilized in smaller systems, are not listed as treatment options under SDWIS (i.e., iron-based adsorptive media).

To supplement these analyses and learn more about treatment options not reported in SDWIS, we made attempts to contact PWS who were in violation for an index year, 2013, and then were compliant in subsequent years (n=63). Of these 63 systems, contact information was found for 31 of them and nine responded. Respondents were asked if any treatments or other technologies had been utilized to help achieve compliance with the FAR following the initial violation.

Monitoring and reporting violations occur when systems i) fail to collect the required number of samples during the specified time frame; ii) fail to ensure the samples are analyzed properly; or iii) fail to submit all required monitoring information.[32] These violations are different from health-based violations that occur when the MCL is exceeded. All violations included in our analysis were due to MCL exceedance. However, additional analysis was conducted to ensure that decreases in health-based violations were not associated with a simultaneous increase in monitoring and reporting violations. Note that only 9–23% of monitoring and reporting violations are actually recorded within SDWIS.[47]

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RESULTS

Temporal Trends for Systems in Violation for Arsenic

The number and proportion of PWS violating the FAR declined dramatically (>50%) since enforcement of the new 10 μg/L MCL in 2006. The maximum number of violations (883) occurred in 2008 and decreased to 348 in 2017 ($p < 0.001$, slope= −0.070). The percentage of PWS in violation declined from a high of 1.3% to a low of 0.55% in the same respective years (Figure 1a). While violations of the older 50 μg/L standard were relatively rare (<0.1%), there was an increase in violations after the new MCL was enforced and PWS were required to adjust their practices and treatments.

Most systems with violations were GW-sourced and/or CWS (Figures 1a, S1). The percentage of GW systems in violation decreased from a high of 1.4% in 2008 to a low of 0.66% in 2017 ($p<0.001$, slope = −0.080), while the percentage of SW systems in violation decreased from 0.35% (2008) to 0.10% (2017) ($p<0.01$, slope = −0.020). Overall, GW systems have far more violations compared to SW systems (Figure 1a). CWS violations decreased at a rate of 0.047% per year ($p<0.01$), and NTNCWS decreased at a rate of 0.081% per year ($p<0.001$). Most violations occurred in very small systems (<500 people served) (Figure 1b). While the majority of systems were in violation for one year (39%), 23% remained in violation for 1–2 years, and 1.8% remained in violation for 12 years (Figure 1c). Table S3 is a summary table of number and percent of violations and mean annual population served by water source, system type, and owner type.

The number of violations was reduced in all system size classes, except for very large (100,000+ served) systems (Figure 1b). Very small systems showed a 55% reduction of systems in violation from the peak year (year with highest number of systems in violation for that system size) to the most recent year (2017); small systems showed a 58% reduction; medium a 69% reduction; and large an 87% reduction.

Temporal Trends for Population Served

The population served by PWS in violation also decreased significantly since enforcement of the FAR. The greatest number of people served by PWS in violation occurred in 2008 at 1.45 million people (Figure 2a). Subsequently, the population served by violating PWS decreased by over 1 million people ($p<0.001$, slope = −106,886). The percent of the population served by PWS in violation experienced a similar reduction of over 70% since 2008 (0.46% to 0.13%, $p<0.001$, slope = −0.036) (Figure 2b). However, there has been a slight, though non-significant, increase in the number and proportion of persons served by violating systems between 2015 and 2017 ($p=1$, slope = 0.0070). This fluctuation appears to be largely due to a single SW system in Texas serving 132,950 people. This system has come in and out of compliance over the years and accounts for over 30% of the people served by PWS in violation in 2017 (Figure 2a). Between 9% and 43% of the people served by FAR-violating systems were served by SW systems.

Prior to 2015, over 50% of the people served by violating systems were served by large to very large systems (between 10,000 and 99,999 served and 100,000+ served, respectively). Since then, there has been a reduction in the discrepancy between size classes (Figure 2a).

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Most of the decrease in people served is driven by a substantial decline in the number of people served by the largest systems in violation, whereas the number of people served by smaller systems in violation for As has not changed much over time. In 2006, 65% (n=865,024) of the people being served by systems in violation were served by large or very large systems. In 2017, only 48% (n=210,396) were being served by such systems. The number of people served by smaller systems in violation decreased by 230,312 since 2006, but they now make up a greater proportion of people served by violating systems.

Overall, large reductions in the proportion of systems violating as well as the population served by these systems were observed. There was no concomitant increase in monitoring and reporting violations, indicating that the observed decrease in health-based violations was not the result of systems avoiding the need to report health-based violations by merely accepting a monitoring or reporting violation (Figure S2).

Geographic Trends in Arsenic Violations and Population Served

Compared to other states, California and Texas had the highest mean annual number of violations and the largest populations served by violating systems over the 12-year period (Table S4). California showed an annual average of 154 violations and 355,938 people served by affected systems, while Texas had 98 violations and 182,591 people served. The states with the highest mean annual proportion of systems violating over the 12 years were Nevada, Arizona, California, New Mexico, and New Hampshire (Table S4). States with the highest mean annual percentage of the population served by violating systems were Idaho, New Mexico, Oklahoma, New Hampshire, and California (Table S4). 15 states showed a 100% reduction of systems in violation from their peak year (year with state's highest number of systems in violation) to the most recent year (2017) (Table S5). California and Texas showed the lowest percent reductions compared to other states (38% and 33%, respectively).

Counties with the highest mean annual violations were primarily in California, Texas, Arizona, New Hampshire, Michigan, and Idaho (Figure 3a). A similar pattern was evident for the highest mean annual population served by violating systems (Figure 3b). Kern County in California was the highest for both metrics, with an average of 32 violations per year and 13,056 people being served by these systems annually. Stanislaus County (CA) and Lubbock County (TX) were far behind Kern County but displayed the next highest annual averages (14 violations and 5,460 served and 14 violations and 5,327 served, respectively). Typically, higher mean violations and populations served were concentrated in certain counties rather than distributed across the state.

Drivers Behind Arsenic Violation Reductions

The total amount of As released annually into the environment, as tracked by EPA'S TRI, declined by 9% per year from 2013–2017 (r^2=0.40), with an overall decline of 45% (Figure 4a). The decline was driven by reductions in releases from the chemical and hazardous waste sectors.

Overall, systems with reported treatment were less likely to be in violation than systems without reported treatment between 2013 and 2017 (Chi-squared p=0.0005). However, when stratifying the violation trends over time by percentage of violators with or without treatment, none of the temporal decline could be explained by documented treatment (Figure 4b). The percentage of violating systems with treatment had not changed significantly ($p=0.97$), while the percentage of violating systems without treatment decreased by 25% ($p<0.01$, slope= −0.028). Additionally, the majority of systems that were in violation in 2013 but were no longer violating in subsequent years did not have reported As treatment (Figure 4c). Note, again, that SDWIS does not capture all As treatment technologies and, therefore, may provide an incomplete picture of rendered treatments. There is also evidence that some systems may be achieving compliance by discontinuing problematic facilities. In our analysis, PWS with higher mean numbers of discontinued facilities appeared more likely to be compliant compared with PWS having lower mean numbers of discontinued facilities, but the differences between these groups each year were not significant (Figure S3).

Nine of the 31 contacted PWS responded to our treatment inquiry. Three had an active form of As treatment installed that was not reported in SDWIS; 3 had switched to an alternative water source; and 3 had either flushed the system, used a blending method, or took no action. Five of the 63 systems initially investigated were found to be inactive.

DISCUSSION

After the initial spike in violations following enforcement of the new MCL, As drinking water violations in PWS have consistently declined across the CONUS from 2008 to 2017. This decline was evident in both GW and SW systems, CWS and NTNCWS, and all system size classes, except for very large systems. In addition, the population served by violating PWS decreased by more than 1 million people since 2008. Compared to the As trend, violations of the MCL for nitrate showed a smaller decline between 2009 and 2016.[42] Considering that there have been significant decreases in urinary As levels among US public water users during this same time period,[35,36] it may be inferred that enforcement of the lower MCL has contributed to the reduction of As exposures to the segment of the US population primarily relying on PWS. This illustrates how federal regulation provides a useful approach for reducing the public's exposure to As. However, this public health benefit does not necessarily extend to people using private wells because they are not regulated by SDWA.

As reported previously,[25,33–36] GW systems are more vulnerable to As contamination than SW systems because of natural geological conditions. Additionally, most violations happen in very small water systems (<500 served). This may be due in part to limited funds or technical expertise available to install advanced treatment processes in some communities.[33,47] Yet, large systems that came into compliance benefited more people even though these systems represent a smaller proportion of total PWS and PWS with violations. For example, one very large SW PWS in Texas serving 132,950 people has had periodic violations and was responsible for the increase in the population served by PWS in violation between 2011 and 2014 and again in 2016 and 2017 (red areas in Figure 2a). Similarly, Pennino et al. found that spikes in the population served by systems violating for nitrate between 2009 and 2016 were also driven primarily by one large SW system.[42] Helping these larger systems adopt adequate treatment may ensure that a greater number of people are protected from drinking water exceeding the 10 μg/L MCL.

While a small percentage of systems (1.8%) remained in FAR violation for the full twelve-year span, most violating systems (73%) did not remain in violation longer than 3 years. This may be due in part to treatments applied by systems to achieve compliance. Systems were less likely to be in violation if they reported treatment. However, our analysis could not determine if reported declines in violations were caused by SDWIS-specified treatments (Figure 4b). Only a small proportion of violators from the 2013 index year became compliant when using treatment in subsequent years while a larger proportion became compliant without treatment. These findings may largely be due to underreporting of treatment. Results from contacting a small sample of PWS violating in 2013 but complying in subsequent years suggest that some PWS operators fail to report treatment to the state or they implement alternative treatments not designated by SDWIS (i.e., blending, purchasing water from another source). Therefore, some of the decline in violations for this group may be due to unreported treatments being initiated or enhancements being made to existing treatment. Other systems may be discontinued in part due to compliance pressures (Figure S3).

Efforts to control As releases to the environment may also be supporting compliance. Analysis of recent TRI data suggests that anthropogenic As outputs to the environment have declined from 2013 through 2017 (Figure 4a). This decline could be contributing to the decrease in violations over time by reducing the level of contamination into source waters, especially for SW which is more vulnerable to anthropogenic input.[7] Further analysis linking contamination in source water with the TRI data by sector, location, and emission pathway (e.g., air, land or water) could strengthen our understanding of how anthropogenic emissions influence drinking water compliance over space and time. However, chemical release information is provided to TRI via self-reporting and is not always consistent with actual releases.[48] Therefore, the reliability of this information may be limited.

As expected, geographical analysis revealed that there are “hot spots” of As drinking water violations and populations served rather than a widespread distribution of occurrence. Violations were more pronounced in the western and southwestern regions that are known to have geological conditions leading to elevated As.[25,26,47,49] There were generally a small number of highly affected counties driving the state mean annual metrics, suggesting that drivers of As violations are localized. To reduce human exposure to levels of As above the MCL, continued action is needed to assess, treat, and monitor sources of As in the drinking water of these areas. This recommendation extends to private well users who do not benefit from FAR and subsequently are responsible for their own drinking water testing and treatment. Interestingly, a recent analysis looking at total health-based drinking water violation trends in CWS (not specific to As) found violation clusters in similar regions to those found in this analysis, indicating that these areas are vulnerable to more than just FAR violations.[47] Correspondingly affected areas included central California, southeast Arizona, southwest New Mexico, and northwest Texas.

A limitation of our study is underreporting within SDWIS. For example, an estimated 26–38% of health-based violations are not reported or inaccurately reported to SDWIS.[47] Additionally, some PWS are in violation of EPA requirements for monitoring or reporting, and the levels of As in their water are unknown. Thus, the extent of As contamination in US municipal drinking water supplies may be underestimated. Another important factor to consider is that SDWIS does not provide violation or population served information at the facility level but rather at the system level, nor does it capture information about non-regulated drinking water sources such as private wells. These limitations hinder the ability to use SDWIS to estimate the population exposed to contaminated drinking water.

Better information is also needed on types and degrees of treatment within SDWIS. The voluntary nature of SDWIS treatment reporting makes it difficult to determine the extent to which treatment technologies have contributed to the overall decline in violations, and some newer technologies considered effective for As removal are not included within the current SDWIS treatment reporting system.[46] Alternative methods may be being used (i.e., blending, switching sources), as shown by PWS operator responses; or those who were initially in violation may be improving their existing treatments to achieve compliance. Future research should further investigate the characteristics of violating systems and compliant systems and which treatment methods are most effective within a local context. While this study only reported on federal violations at the 10 μg/L level, closer examination of states with more stringent MCLs, such as New Jersey, may also be helpful for understanding how lower As standards could be implemented to protect human health.

Arsenic exposure has serious health implications and minimizing opportunities for exposure will mitigate risk. Since drinking water has historically been the primary route of exposure for humans, reducing As in PWS is an important public health intervention strategy. This analysis demonstrates that the 2001 regulation initiating the lowered target has been successful in reducing the population served by systems in violation of the 10 μg/L As MCL by over 1 million people and may be a major factor in reduced human exposures.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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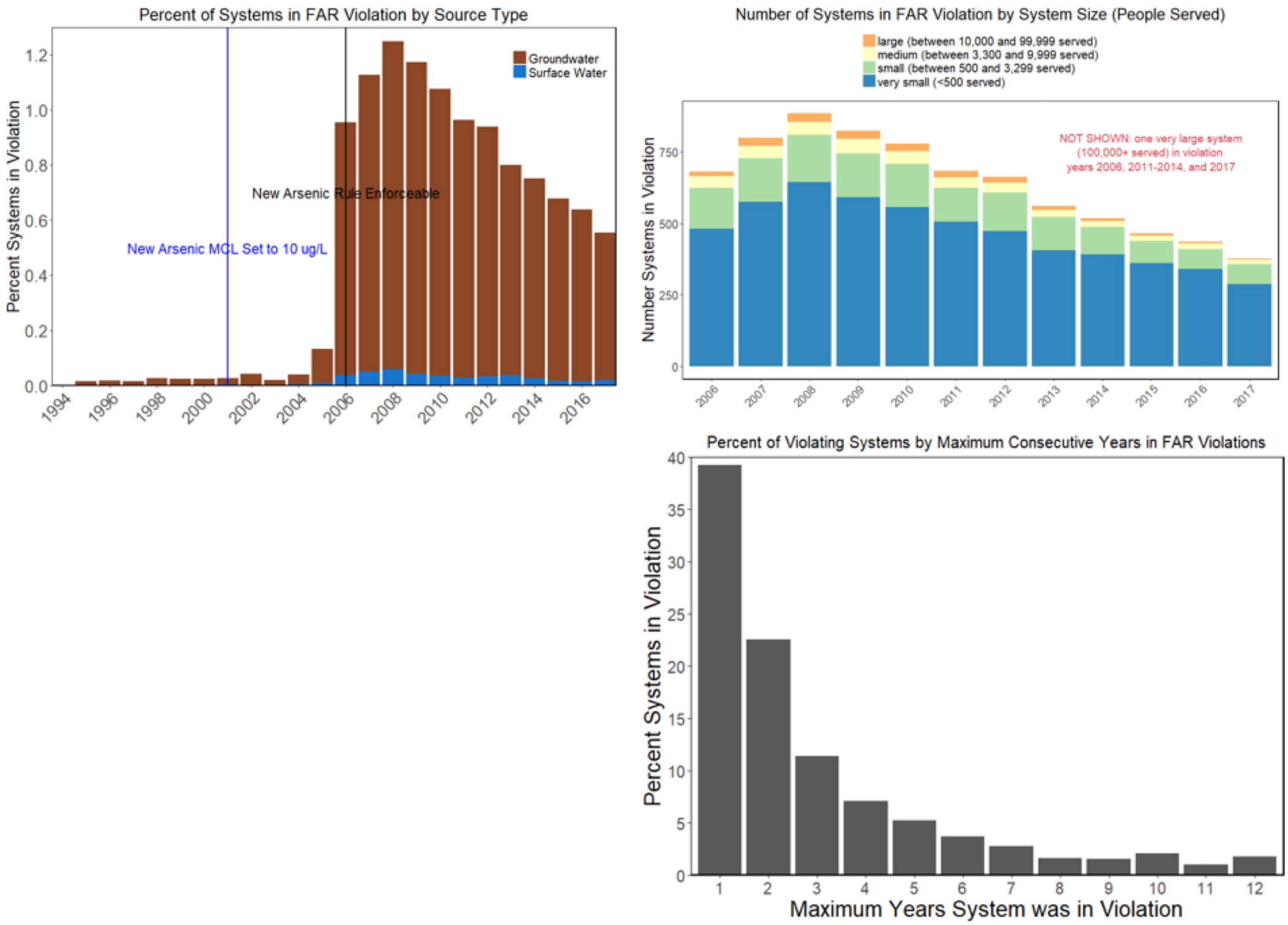

Figure 1.

(a) ***(top left)*** The percent of U.S. PWS (CWS and NTNCWS) in violation for arsenic (exceedance of MCL) by source type between 1994 and 2017; **(b)*****(top right)*** The number of U.S. PWS (CWS and NTNCWS) in violation for arsenic (exceedance of MCL) by system size between 2006 and 2017; **(c)** ***(bottom right)*** The percent of U.S. PWS (CWS and NTNCWS) in violation for arsenic (exceedance of MCL) by maximum consecutive years in violation.

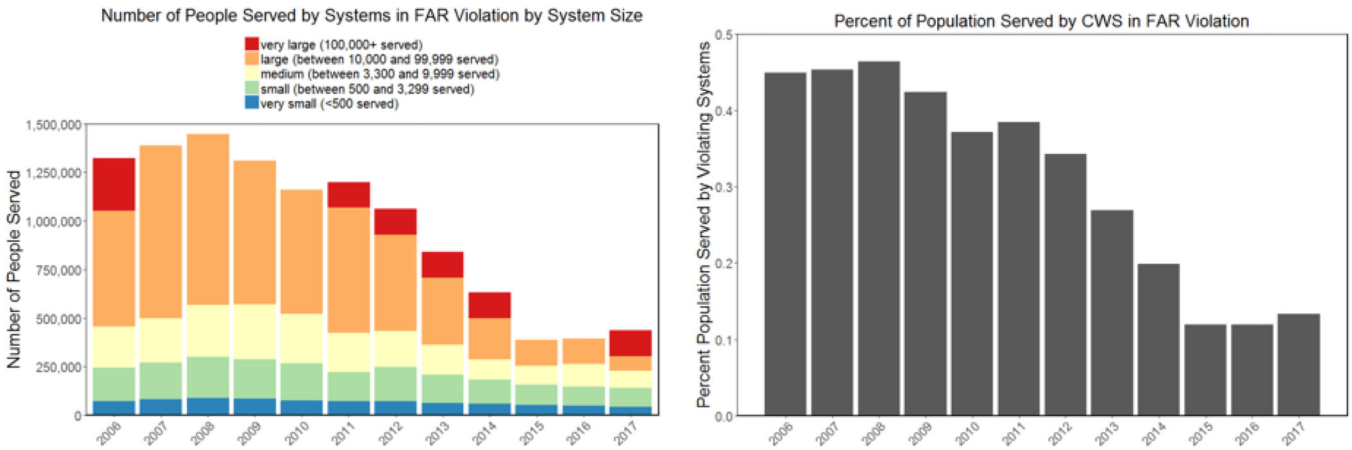

Figure 2.

(a) ***(left)*** The number of people served by U.S. PWS (CWS and NTNCWS) in violation for arsenic (exceedance of MCL) between 2006 and 2017 by system size; **(b)** ***(right)*** The percent of the population served by U.S. PWS (CWS only) in violation for arsenic (exceedance of MCL) between 2006 and 2017. The denominator is comprised of the total population served by CWS (does not Include people served by non-public sources, such as private wells).

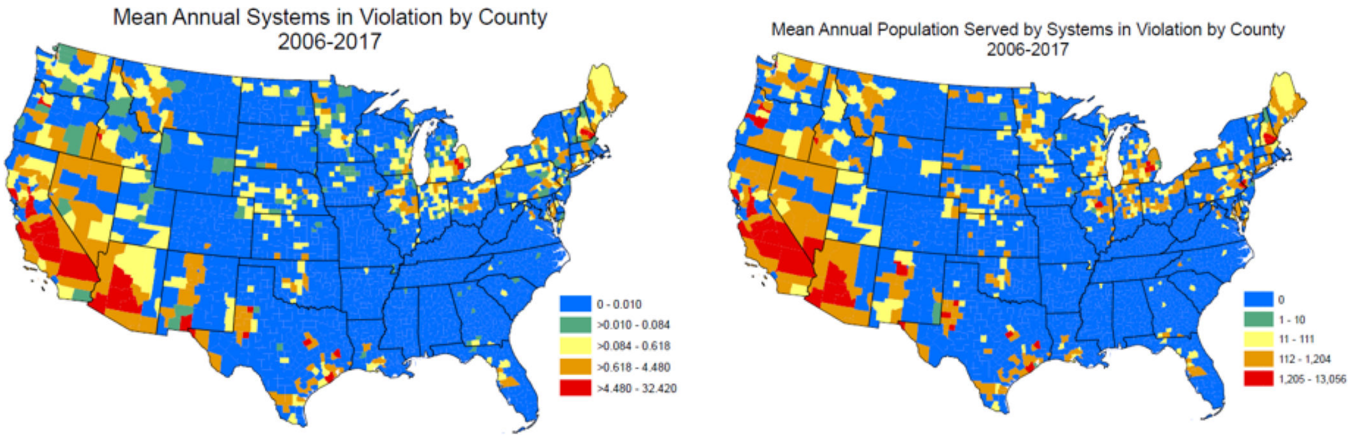

Figure 3.

(a) ***(left)*** The mean annual number of PWS (CWS and NTNCWS) in violation for arsenic (exceedance of the MCL) by county; **(b)** ***(right)*** The mean annual population served by PWS (CWS and NTNCWS) in violation for arsenic (exceedance of the MCL) by county.

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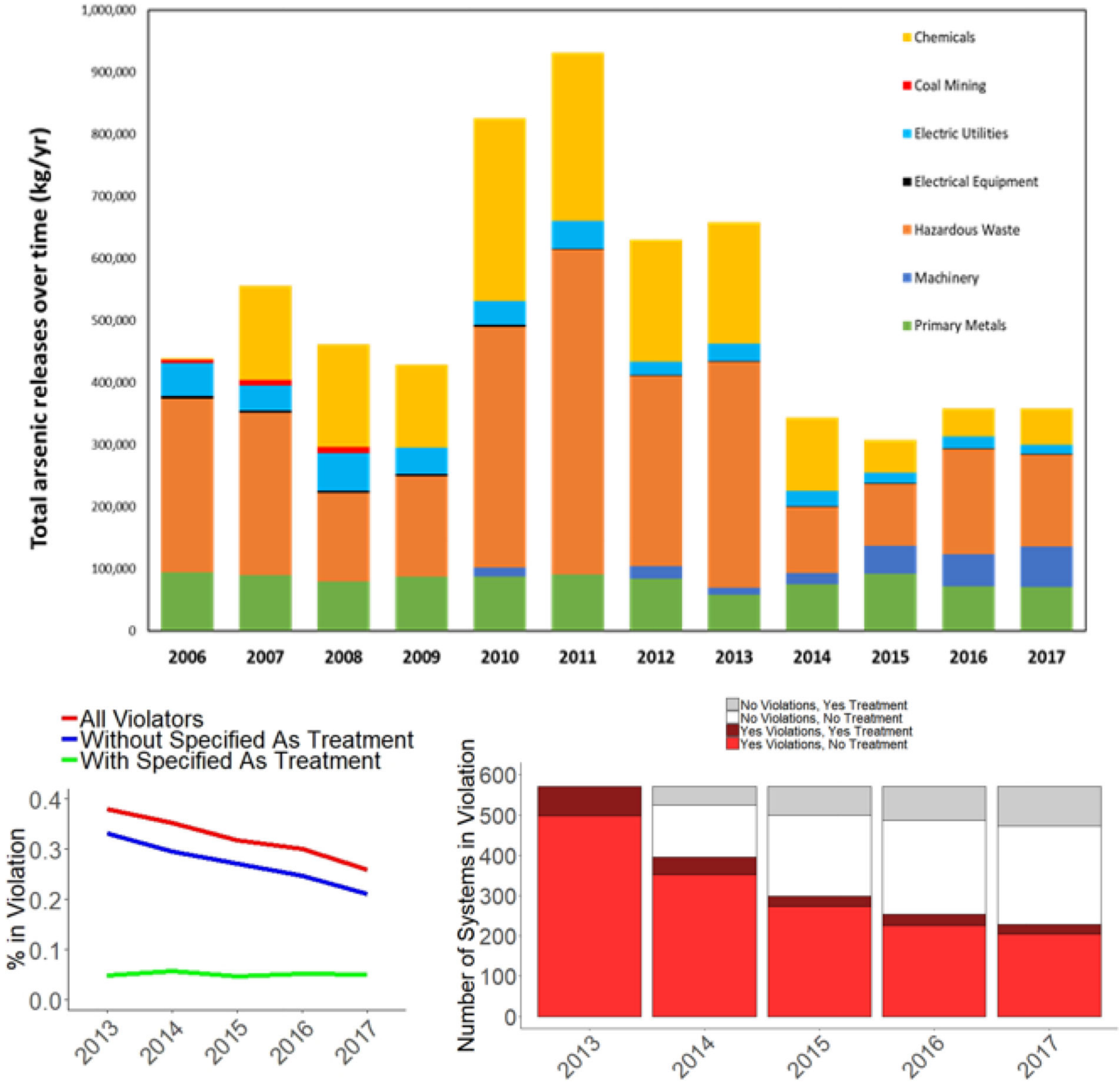

Figure 4.

(a) ***(top)*** Total arsenic releases to the CONUS as tracked by the Environmental Protection Agency's Toxic Release Inventory from 2006 to 2017. The y-axis indicates arsenic released in kilograms/year; **(b)** ***(bottom left)*** The percentage of PWS in FAR violation from 2013 to 2017 with groups stratified by treatment report or no arsenic (As) treatment report. PWS with treatment NAs for certain years were included in the model. "Specified" treatments are those which are reportable in SDWIS and considered effective for arsenic removal (Table S2); **(c)** ***(bottom right)*** Baseline group of PWS in FAR violation starting in index year 2013 and progressing to 2017. PWS in violation without treatment are indicated in light red; PWS in violation with treatment in dark red; PWS no longer in violation without reported treatment in white; and PWS no longer in violation with treatment in gray.