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# Lessons Learned from Arsenic Mitigation among Private Well Households

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## Abstract

**Purpose of Review—**Many thousands of research papers have been published on the occurrence, health effects, and mitigation of arsenic in drinking water sourced from groundwater around the world. Here, an attempt is made to summarize this large body of knowledge into a small number of lessons.

**Recent Findings—**This is an opinion paper reflecting on why we are far from the goal of eliminating this silent and widespread poison to protect the health of many millions. The lessons are drawn from research in countries representing a range of economic development and cultural contexts. The replacement of household wells with centralized water supplies has reduced population level exposure to moderate (50–100 μg/L) and high (>100 μg/L) levels of arsenic in drinking water in some countries as they become wealthier. However, there remains a very large rural population in all countries where the exposure to low levels (10–50 μg/L) of arsenic continues due to its dispersed occurrence in the environment and frequent reliance on private well. A set of natural (geological and biological), socioeconomic, and behavioral barriers to progress are summarized as lessons. They range from challenges in identifying the exposed households due to spatially heterogeneous arsenic distribution in groundwater, difficulties in quantifying the exposure let alone reducing the exposure, failures in maintaining compliance to arsenic drinking water standards, to misplaced risk perceptions and environmental justice issues.

**Summary—**Environmental health professionals have an ethical obligationtohelpAsmitigationamongprivatewellwaterhouse-holds, along with physicians, hydrogeologists, water treatment specialists, community organizations, and government.

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Compliance with Ethical Standards

**Conflict of Interest** Yan Zheng declares that she has no conflict of interest.

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**Keywords**

Arsenic; Groundwater; Spatial heterogeneity; Optimistic bias; Environmental justice; Drinking water safety; Socio-economic development

## Introduction

Arsenic (As) is one of the World Health Organization (WHO)'s 10 chemicals of major public health concern, with a WHO recommended drinking water guideline value of 10 μg/L [1]. Chronic exposure to As in drinking water has been shown to result in skin, bladder, and lung cancers, as well as a variety of adverse non-cancer health outcomes, including cardiovascular disease, diabetes, non-neoplastic respiratory changes, and neuropathy [2–4]. Especially troublesome is arsenic exposure in utero and during early life [5] which has resulted in a magnitude of effect not yet found for any other environmental exposure [6]. The negative outcomes include reductions in IQ [7], increased mortality from acute myocardial infarction later in life [8], and significantly increased risk of death from lung cancer and pulmonary disease as a young adult.

Arsenic is a minor element in the Earth's upper crust with an abundance of 4.8 mg/kg [9], with its mobility in groundwater primarily controlled by redox conditions when pH is circumneutral [10]. In addition to arsenic enrichment in many low-lying unconsolidated sediment aquifer systems where the reducing conditions prevail [11], hot springs and acid mine drainage sourced arsenic have been known to pollute down gradient surface water bodies [12–14]. Given that As is not rare in nature and that reducing groundwater is quite common, many areas of the world relying on groundwater for drinking are therefore at risk of having a sizeable As exposed population. Not only the likelihood of its occurrence has been assessed by geostatistical models [15–19] but also various degrees of geogenic As problems have also been reported in over 70 countries affecting an estimated >100 million people's drinking water supply [20]. However, the population exposed to As globally is still not well defined due to incomplete testing of hundreds of millions of mostly private household wells, which, unlike public water supply, are not required to meeting drinking water quality standards in most countries.

What lessons have been learned from many years of research centered around occurrence, hydrogeochemistry, and health effects of As? This paper aims to critically assess such available knowledge to shed light on issues relevant to exposure reduction that may be worthy of sustained attention, with different degree of emphasis to suit a particular country's context. The hope is that these lessons will stimulate discussions among environmental health professionals who have more experience in dealing with exposure reduction of anthropogenic sourced pollutants, in contrast to naturally occurring arsenic for which there is usually no villain to blame. In order to overcome the challenges presented by the tasteless, odorless, and naturally occurring As in drinking water affecting mostly dispersed rural populations, environmental health professionals who hope to act on this hazard may find it helpful to consider these lessons and to expand on them.

# Part I. Lessons from Spatially Heterogeneous Arsenic Distribution in Groundwater

## Lesson 1. Work with Hydrogeologists to Identify Arsenic-Safe Groundwater for Water Supply

Population level exposure reduction has been made possible through careful "mapping" to delineate where low As groundwater exists [21], augmented by research that illustrates how such water can be utilized reliably for individual or communal water supply to avoid arsenic [22]. The mapping is necessary because the vast majority of As in drinking water supply is due to its occurrence in groundwater which is drawn from an *x-y-z* (longitude, latitude, and depth) point subsurface. Such low As zones in groundwater systems have been observed throughout South and Southeast Asia [23]. However, the vulnerability of these zones if the water is pumped out at high rates such as for irrigation use or municipal supply, would still require careful assessment [24–26]. It has been shown, for example, that the deeper Pleistocene low As zones in Bangladesh can be tapped for drinking although using it for irrigation is not recommended [27]. Although the *x-y* coordinates of a water point can now be measured within <10-m precision by any GPS enabled devices, the *z* coordinate (depth) is more prone to error because it is often based on self-reporting unless the wells have been registered with government agencies and can be verified by a drilling record—this is not always the case even in the USA [28].

When utilizing a low As water source to avoid As, it is prudent to monitor As concentrations annually, especially for private wells located in areas where As is known to occur. Large volume pumping in surrounding aquifers has been shown to induce changes in groundwater flow patterns, which in turn, induce variations in As concentrations. For example, the US Geological Survey examined five hydrologically distinct aquifer systems in the USA and found that increases in well water arsenic levels from the Floridan aquifer near Tampa, Florida, and the sedimentary aquifers in eastern Wisconsin were due to large volume pumping by nearby public supply wells [29]. Further analysis of factors affecting temporal variability of arsenic in US groundwater confirm that arsenic concentrations mostly vary by small amounts (only 11% of wells show increases or decreases in concentrations of arsenic ≥ ± 4 μg/L), but concentrations in public supply wells vary more than in private domestic wells [30].

## Lesson 2. One High As Value Means that there Are Other Non-compliant Wells Nearby

The spatially heterogeneous arsenic distribution patterns have been qualitatively described as exhibiting "point" characteristics at local scale ($10^1$–$10^3$ m) and "belt" or "cluster" characteristics at regional scale ($10^3$–$10^5$ m). The truth is that we still do not know what hydrogeological and biogeochemical processes are responsible for such patterns and how they might evolve with time. With colored dots representing low, medium, high, to very high levels of well water As, the resulting As point spatial distribution map can appear to be more like a Monet painting than actual data [21, 31, 32]. Because the locations of wells are determined by where people live and use groundwater and are not designed to be part of a representative sampling program to ascertain mechanisms regulating As spatial patterns which can benefit from an equal area grid sampling approach [33], this makes the science of understanding the underlying causes for the spatially heterogeneous arsenic distribution patterns very challenging. For example, even the simple task of describing the variability at various spatial scales suffers from uneven sample distribution and inadequate sampling density (Table 1).

Despite such challenges, we have done enough surveys in enough places with a range of spatial sampling density and distribution patterns to know that if by chance a survey finds a high As well, it is inevitable that many more wells with lesser yet still not in compliance As levels are nearby. This is because the distribution of arsenic concentrations within a given geographic region is highly skewed (Table 1). So, when testing identifies a well with very high As of >100 μg/L, it means there will be more nearby wells that will have 10–100 μg/L of As. On the contrary, testing one well in a given area and finding not-detectable As (in most cases <1 μg/L of As) should be interpreted with great caution because the chance of finding not-detectable As in an area with higher levels present can be as large as >80% (Table 1). Given the high likelihood of not detecting As in most local surveys, it would be prudent to test at least 10 samples in the same hydrogeologic unit to have a better chance of not missing the above 10 μg/L of As sample. We wish we knew more about how many wells in 1 $km^2$ should be sampled to obtain a representative, stable, or more “true” As distribution for that 1 $km^2$ area, and even then, this still needs to be interpreted considering the hydrochemical settings of the aquifer. A sampling density of 1–5/$km^2$ is found to be sufficient to capture the groundwater As occurrence rate in fractured bedrock aquifers of New England at the intermediate spatial scale ($10^3$–$10^4$ m). However, to do the same at local scales of <$10^2$ m, higher sampling density of 10 s of wells per square kilometer is desirable [28]. Thus, the occurrence of a very high As well should justify a public health action plan to test all nearby wells within 1 km of its radius and/or in the same hydrogeologic unit.

## Part II. Lessons from Exposure Assessment and Reduction

### Lesson 3. Always Test, Even with Field Test Kits to Enable Testing among the Rural Poor

Given the spatial heterogeneity, the only reliable way to determine whether a water sample is compliant with a drinking water standard is to conduct a test, yet how reliable that test is depends on not just the capabilities inherent in the laboratory methodologies but also those of the samplers and testers. This also means that sampling protocols should include sufficient numbers of blanks to trace sources of artificially introduced contamination, replicates, and blind quality assurance (QA) and quality control (QC) samples to monitor and to minimize human errors. The most sensitive and precise modern instrumentation method for As analysis is the high-resolution inductively coupled plasma mass spectrometry (ICP-MS). When it was employed by highly skilled research scientists in a controlled laboratory setting [36], the blanks were still 0.08 μg/L of As when the highest purity acids were used to pre-treat samples and the detection limit was 0.07 μg/L of As. Repeated analysis of a natural water standard (NIST 1640) with a certified As level of 26.67 μg/L yielded As concentrations of 26.3 ± 0.5 μg/L of As ($n$ = 26), a precision of 2%. In practice, because blanks could be higher and more variable, instrument settings could fluctuate beyond what can be controlled by internal standards, the detection limit and precision can only be worse than the aforementioned. For example, the 2009 Bangladesh drinking water quality survey employed a conventional ICP-MS method for analysis through a reputable Canadian commercial testing laboratory which reported a method detection limit of 1 μg/L of As, although the blanks collected along with water samples in the field averaged 0.53 μg/L of As after excluding 21(10.3%) out of the 203 labeled blanks because the excluded blanks showed very high As values which were attributed to mislabeling [34]. Thus, in practice, As concentrations can probably be ascertained to 1 μg/L with a precision of around 10% assuming human errors are being properly dealt with.

The errors inherent in As laboratory analysis despite best practice means that there will always be some mis-classification of whether a water sample is in compliance around the current 10 μg/L of As standard adopted by many governments. With the lowering of drinking water standards to 5 μg/L of As by some governments, the likelihood of misclassification becomes even higher. In light of this, even though the commercial test kits are meant to be qualitative, it is remarkable how well they have performed in real-world settings. When the ITS Econo Quick As test kit was used by highly trained hydrogeologists in Maine to test 25 pairs of raw and treated private well water, there is only one non-matched result: a sample with 7 μg/L of As determined by HR ICP-MS analysis had a test kit reading of about 25 μg/L [37]. The same test kit was used in Bangladesh to test 123 wells by locals who were trained and hired to be testers by an NGO. Relative to 10 μg/L of As, the kit underestimated 11% of the samples and overestimated 0% of the samples; relative to 50 μg/L of As, the kit both underestimated and overestimated 4% of the samples, when compared to HR ICP-MS measurements [38]. It is worth noting that usually, under or over estimates are not more than one category apart so the kit is still useful in identifying hazard [39]. All things considered, because millions of wells remain untested, a wider range of testing methods including field test kits should be considered and even recommended to community organizations interested in testing, especially for screening purposes in rural areas where poverty concentrates. It is of course useful to have laboratory tests to confirm the test kit results and to ascertain other water chemistry parameters, especially in high-income countries where the next action is to treat water. The test kits have the additional advantage of "visualizing" the invisible hazard As among the private well households and are immediately available to the concerned; although how this may impact the risk perception of individuals has not been studied.

## Lesson 4. Test a Biomarker, Analyze Arsenic Species when Urinary Total As is Above 15 μg/L

Due to its long latency for some health outcomes, assessment of lifetime exposure to arsenic is a critical task for epidemiologists interested in evaluating health effects. However, for the purpose of evaluating exposure reduction, the task is simpler because a comparison of urinary arsenic levels among the exposed before and after access to As-safe water is usually sufficient. An additional advantage of biomonitoring is that health insurance may cover the cost of urinary arsenic tests in most high-income countries should a physician request it, whereas in most cases, a water arsenic test has to be paid for by the well owner. Yet, physicians would need a medical reason to request testing. Further, interpretation of urinary *total* As level is fraught with complications from dietary arsenic intake and from metabolism of inorganic As to organic As species. It is only until very recently that careful analysis of urinary As speciation data in large populations illuminated what may be considered "normal" urinary arsenic composition as well as the total As level [40••]. Taking advantage that urinary arsenobetaine is a specific biomarker for seafood intake and is excreted without being metabolized, As speciation analysis results of urine samples from the Multi-Ethnic Study of Atherosclerosis (MESA, $n = 310$) and the 2003–2006 National Health and Nutrition Examination Survey (NHANES, $n = 1175$) participants showed that the median value of urinary total As level is 8.1 and 5.1 μg/L before and 3.1 and 2.5 μg/L after the seafood-sourced As signal was removed, respectively. Because the study subjects in MESA are from urban places in the USA and in NHANES they are from both rural and urban US areas, hence likely, a representative sample of the US population and are not known to have been exposed to drinking water-sourced As, it is not surprising that even at this normal urinary total As level, subjects who consumed rice more than twice a week displayed 1.75 times higher seafood-free urinary As geometric mean values than those who never or rarely consumed rice. Although more studies in other populations on what is considered normal and ways to correct for seafood "interferences" would be valuable, it appears that if a person's total urinary As level is above 15 μg/L, the 75th percentile uncorrected value of the MESA cohort, then it is reason enough to trigger a test of As in the drinking water of the person, and if possible, urinary As speciation.

Among arsenic-exposed populations, mitigation interventions have indeed led to reduction in urinary total arsenic level. In Guizhou, China, where villagers were exposed to very high levels of As in their diet through consumption of As-contaminated chili peppers and corn dried over unventilated stoves that burned coal containing high levels of As, a government-led intervention effort that included closing of high As coal mines and introduction of ventilated stoves lowered the urinary total As levels by a factor of 4 among arsenicosis patients and the control group [41]. In San Pedro de Atacama, Chile, the mean value of urinary total As level of residents ($n = 73$) decreased from 636 to 166 μg As/L after they were provided with drinking water containing ~45 μg As/L for 2 months [42]; the urinary As speciation profiles were mostly similar except for a small decrease in %inorganic As and MMA/DMA ratio post intervention. In Araihazar, Bangladesh, the baseline urinary As level in participants ($n = 11,746$) in a prospective cohort study averaged 375 μg As/g creatinine. Later, the urinary As level of those who reported switching to a well identified as meeting Bangladesh drinking water standard of 50 μg As/L dropped to an average of 200 μg As/g creatinine [43]. The urinary As level in micrograms per liter is roughly one half of the micro-gram As per gram creatinine. While this reduction of As exposure is encouraging, it is clear the Bangladesh population has a much higher arsenic burden (Table 1) even if the country manages to supply water at <50 μg As/L to all.

## Part III. Lessons from Maintaining Compliance to Arsenic in Drinking Water Standards

### Lesson 5. The Smaller the Water Supply, the Higher the Failure Rate of Arsenic Treatment

US EPA has carried out demonstrations of arsenic treatment technologies [44] such as coagulation/filtration, adsorptive media, ion exchange, and iron removal systems to assist water utilities to select cost-effective ways to remove arsenic to below 10 μg/L level [45].

Coagulation/filtration was successful at the city of Los Angeles where source water had 22 μg As/L [46] and at the city of Antofagasta in Northern Chile [47] where source water was ~870 μg/L between 1958 and 1970 [48]. Although coagulation/filtration is an excellent method for treating arsenic sourced from surface water due to its efficient removal of inorganic As(V) for municipal water supply [49], it is not suitable for household water treatment due to the large space requirement.

The smaller the water supply system, the less it will benefit from the suitability of coagulation/filtration and the economy of scale. Not only this increases the cost for each person supplied but also introduces many opportunities for failure due to lack of human capacity. In September 2016, the Environmental Integrity Project reported that 95 community water systems in California serving more than 55,000 people, many are poor and/or Latino or African-American clustered in the San Joaquin Valley, are still providing water with >10 μg As/L. In addition to conflicting county and state rules, many local water districts there struggled with indecision or a lack of money to supply safe water.

The smallest water supply is a private well, thus odds are against its treatment success. Additionally, reducing groundwater tend to have more inorganic As(III) and competing anions that interfere with As treatment than surface water, hence more difficult to treat [50]. This has led to ongoing efforts to optimize oxidation As(III) to As(V) as pretreatment [51] and a search for better adsorptive media [52–54] because reverse osmosis (RO) performs poorly in removing inorganic As(III) [55]. Based on practical experience, the New Jersey Department of Environmental Protection recommends granular ferric adsorption whole house system with one worker tank followed by a safety tank [56], along with monitoring of the treated water after the worker tank to ensure safety. This type of system costs on average US$2740 in 2007 dollars to install, the media last 2–3 years before needing replacement, and maintenance costs US$0.67–1.00/day. Although cost-effective As treatment technologies are available on the US market [57], it is nevertheless an unregulated market so consumers are left on their own to solve a complex water treatment puzzle. Without the necessary technological expertise afforded by the larger water supply system, the reality is some who have installed an As treatment unit still ended up not being able to obtain As safe-water for a variety of reasons that include the consumers tendency to favor Point-of-Use (POU) RO which is the least reliable technically, although it should be noted that treated water in most cases is significantly improved (Table 2).

## Lesson 6. Pay Attention to Biological, Behavioral, and Socioeconomic Vulnerabilities

In many ways, exposure reduction efforts to date have not carefully differentiated another kind of heterogeneity: even when the potential exposure dose is the same, research has identified biologically, behaviorally, and socioeconomically vulnerable groups. Work has only just begun to evaluate the implications of such heterogeneity because different groups will likely need different kinds of help to reduce exposure [63••]. For example, US doctors caring for pregnant women on private well water are not advising testing of drinking water en masse, so it is even less likely that a urinary As test will be ordered, even in high-risk areas. The American Academy of Pediatrics has issued a policy statement that called for pediatricians to encourage private-well households with children to test their water [64]. Yet, our surveys in Maine find that only 14% of households with children cite their children as a main reason for having tested their well water, indicating that testing recommendation may not be passed along by pediatricians.

Researchers have also probed into the behavioral or psychological factors behind health protective actions of private well households in Bangladesh [65–69]; Ireland [70]; Ontario [71–73] and Nova Scotia [74, 75] of Canada; and Maine [37, 76], Montana [77], New Jersey [78•, 79, 80], Nevada [81, 82], Washington [77], and Wisconsin [83] of the USA. A common thread emerged from these studies is an optimistic bias whereby perceived risks are lower than objective risks [84], resulting in a heterogeneous response among exposed households in that some do not act to reduce exposure. A silver lining is that the probability of acting to mitigate As once the test results are disseminated to households increases with the level of As in Bangladesh [85], and in Maine [37], where 31% of households exposed to 10 and 50 μg As/L did not act, compared to 11% of households with well water >50 μg As/L. A systematic review of the literature (>14,000 documents) [86] examining the efficacy of the use of water quality information dissemination at changing either household or community water management behavior could only identify six studies that met inclusion criteria, four of which were on As in Bangladesh, where 26–72% among those who received a positive test result switched to an As-safe source [43, 87–91]. Subsequent studies that applied the RANAS (risk, attitude, norm, ability, and self-regulation) model of behavior change to examine safe water use behaviors [67, 68], especially well switching in Bangladesh, has found that switching to an arsenic-safe water source was significantly associated with increased instrumental attitude, descriptive norm, coping planning, and commitment [92], although the switching rate declined over time [66]. When the same RANAS model was applied in Maine, the belief that the untreated water is not safe to drink (risk) and that reducing drinking water As would increase home value (instrumental attitude) were identified as significant predictors of mitigating As [37]. Although interventions targeting the behav-ioral barriers have shown promise [65, 66], it is far from certain that every exposed household can be "persuaded" to take action if not required by an authority to do so.

There is also an environmental justice issue in that lower income and less-educated groups are more affected by As in private well water. The most comprehensive study to date investigated this vulnerability in Maine and New Jersey and found that although there is no evidence for lower socioeconomic status groups disproportionately residing in areas with arsenic, disparities in exposure arise from differing rates of protective behaviors as well as psychological factors favoring such behaviors [80]. In Arizona, residents with higher income and education levels are more likely to treat water [61]. Likewise, level of education had a positive effect on the decision to avoid arsenic exposure in rural Bangladesh [69]. In New Jersey, a state law requiring arsenic to be tested during real estate transaction had a fortunate effect to partially address the socioeconomic disparity in voluntary testing [78•, 79].

From the ethics perspective, it is not right to knowingly expose a fraction of private well population to a poison. It also does not sit well while some countries are requiring more protective drinking water quality standards as low as 5 μg As/L while others are still using 50 μg As/L. From the policy perspective, the benefits of New Jersey's Private Well Testing

Act have led to a call for universal screening of private well water quality achieved through enacting more state and local government testing laws in the USA [63••]. The current laissez-faire approach adopted by most countries in managing private well water quality fails to address the multiple vulnerabilities.

## Conclusion: The Way Forward

The United Nation's proposed indicator of "safely managed drinking water services" calls for tracking the population accessing drinking water which is free of fecal contamination and priority chemical contaminants, including arsenic. Environmental health professionals can and should help address the dispersed low-level arsenic exposure among the rural poor in many countries. They can work more closely with physicians to encourage more testing of well water and urinary arsenic, support community groups to test well water using any reliable means rather than just laboratory methods, lean on hydrogeologists to plan their survey and to identify arsenic-safe groundwater source, and engage water treatment professionals to recommend best practices in maintaining treated water compliance. Lastly, government clearly has a role to play to ensure safety of the private water supplies relied on by a significant portion of the population, through looking at appropriate levels of regulations of both the water testing and water treatment. All people, independent of water source, should be protected from involuntary exposure to arsenic.

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## Table 1

Summary statistics of water As data based on selected surveys

| | Bangladesh[a] | | | | USA[b] | | China[c] |
|---|---|---|---|---|---|---|---|
| **Parameter** | **MICS2009 (ICP-MS)** | **MICS 2009 (Arsenator)** | **BGS 2001** | **Araihazar** | **USGS nationwide** | **Central Maine** | **Yinchuan Plain** |
| Area ($km^2$) | 147,610 | 147,610 | 147,610 | 25 | 7,663,941 | 1135 | 7300 |
| Sample (*n*) | 2904 | 13,971 | 3534 | 4972 | 20,043 | 1432 | 761 |
| Sample density (/$km^2$) | 0.02 | 0.09 | 0.02 | 199 | 0.003 | 1.3 | 0.10 |
| [As] µg/L | | | | | | | |
| Level of detection | 1.5 | 8.6 | 0.5 and 6 | 5.0 | 1.0 | 0.5 | 1 |
| 25th percentile | 0.5 | 0.0 | 0.5 | 6.3 | 1.0 | 1.2 | 1 |
| Median | 0.5 | 0.0 | 3.9 | 55.0 | 1.0 | 4.6 | 1 |
| 75th percentile | 4.0 | 18.0 | 50.0 | 141.6 | 4.0 | 14.9 | 3 |
| Mean | 17.7 | 27.1 | 55.3 | 97.0 | 7.4 | 13.9 | 7 |
| % samples | | | | | | | |
| 0–5 | 77.4% | 59.0% | 52.0% | 23.4% | 81.1% | 52.4% | 83.3% |
| 5.1–10 | 4.8% | 8.8% | 5.9% | 4.8% | 7.7% | 14.1% | 4.1% |
| 10.1–50 | 9.4% | 18.8% | 17.2% | 20.0% | 9.3% | 27.7% | 10.0% |
| 50.1–100 | 4.8% | 7.2% | 8.9% | 16.7% | 1.1% | 4.3% | 1.5% |
| >100 | 3.7% | 6.1% | 16.0% | 35.1% | 0.8% | 1.5% | 1.2% |

Data Source:

[a]Bangladesh: MICS 2009 [34], BGS2001 [31], and Araihazar [21]

[b]USA: USGS Nation Wide [32], Central Maine [17]

[c]China: Yinchuan Plain [35]

**Table 2**

Selected evaluation of household arsenic treatment system in real-world situation

| | Untreated well water | | | Treatment system | | | |
|---|---|---|---|---|---|---|---|
| **Place** | **Sample (*n*)** | **Max As (µg /L)** | **% >10 µg As/L** | **Sample (*n*)** | **Type** | **Performance** | **Refs** |
| Lahotan Valley, Nevada | 262 | 870 | 71% | 59 | RO | Raw water displayed 4 to 4100 µg As/L (median 103). Treated water had <3 to 180 µg As/L (median), with 18 or 30% not in compliance | Walker 2008 [55] |
| Western Nevada, USA | 132 | 2362 | 80% | 19 | POU RO | Raw water displayed 36 to 2363 µg As/L (mean 443). Treated water had <10 to 641 µg As/L (mean 87), with 10 or 53% not in compliance | George 2006 [58] |
| SE Michigan, USA | 142 | 99 | 26% | 19 | POU RO and Softner/RO | Raw water displayed <0.1 to 28.5 µg As /L (mean 5). Five untreated water had >10 µg As/L became compliant after treatment | Slotnick 2006 [59] |
| Massachusetts, USA<br>Maine, USA<br>New Hampshire, USA<br>New Jersey, USA | 21<br>128<br>73<br>53 | 100–300<br>375<br>447<br>100–300 | 71%<br>86%<br>89%<br>40% | 275 | npXtra™ POE (n = 236) and POU (n = 39) | Manufacture field testing POE and POU with NSF/ANSI 61 certified adsorption media (ArsenXnp®) consisting of hydrous iron oxide nanoparticles impregnated into a polymer bead capable of removing both As(III) and As(V). Sampled at installation, every 6 months for POU and every 9 months for POE over 1.5 years. Some POE systems began to show signs of breakthrough in the worker column after 1.5 year of use and were replaced | Moller 2009 [57] |
| N Carolina, USA | 1 | 9 | 0% | 1 | 3 types | Compared a POE sediment trap, a POU RO system, and a POE and POU granulated ferric oxide (GFO) filters to treat a well water with 4 to 9 µg / LAs. POUROlowered treated water As to between 0.1 and 1 µg /L As, POU GFO reduced As to <0.01 µg/L As and costs ~US$400 to install and US$80 to replace the filter annually. | Pratson 2010 [60] |
| Central Maine, USA | 99 | 345 | 100% | 25 | POU RO + Adsorbant | Of 99 HHs self-reported to be treating for As, inspection found 26 HHs mistakenly thought their sediment filter or water softner treatment was for As. In a subset of 25 HHs, As was analyzed by HR ICP-MS for untreated water (range: 7 to 315 µg/L, mean 85) and for treated water (range: 0.1 to 240 µg/L, mean 26). Of 68 HHs using an As treatment system (51 of which were POU RO), 15% were not in compliance based on Econo Quick Test Kit results | Flanagan 2015 [37] |
| Central Arizona, USA | 16 | 251 | 37.50% | 5 | POU RO | Raw (treated) water [As] in 5 HHs are 2.2 (2.6), 2.5 (0.03), 13 (7.9), 48 (1.2), 119 (18.6). 20% post-treatment not in compliance | Lothrop 2015 [61] |
| Cornwell, UK | 497 | 440 | 5% | 2 | Unknown | Raw water displayed 14 and 49 µg As/L, also high Fe (11,000 and 1500 µg /L). Treated water had 1.0 and 0.1 µg As/L | Ander 2016 [62] |

*POU* point-of-use; *POE* point-of-entry, *RO* reverse osmosis