Arsenic Removal from Drinking Water: Experiences with Technologies and Constraints in Practice

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Abstract: Treatment of drinking water for arsenic (As) removal has been implemented in centralized facilities worldwide, reflecting the increasingly stringent national and international drinking water standards for As, for which a standard of 10 μg/L has been widely adopted. It might therefore be expected that information on the performance of installed treatment processes could serve as basis for process optimization and more-informed decisions on process selection. A review of available information on installed treatment does provide some insight into the scale of implementation, factors driving process selection and difficulties that have arisen in practice (as a complement to more accessible information on bench-scale and pilot-scale studies). The availability of information on treatment performance at full-scale treatment is, however, severely limited. The rapid advances in information technology and consequent elimination of technical barriers to sharing information and knowledge should allow the development of an international, accessible database or even a metadata portal for installed technologies for As removal that would offer the potential to benefit from past and ongoing experience in practice. **DOI: 10.1061/(ASCE)EE.1943-7870.0001225.** *This work is made available under the terms of the Creative Commons Attribution 4.0 International license, http://creativecommons.org/licenses/by/4.0/.*

Introduction

Concern over the occurrence of arsenic (As) in drinking water has a long history. The effects of chronic As exposure have been well documented and have provided the basis for regulating As concentrations in drinking water (NRC 1999; U.S. EPA 1988). In the United States, a limit of 50 μg/L was first set for As in 1942 and is still the standard in some countries today (Mondal et al. 2013). In the mid-1990s, the human health effects of chronic As exposure in South Asia attracted international attention (Bagla and Kaiser 1996). Many countries, including the United States, adopted a standard of 10 μg/L in the early 2000s (Mondal et al. 2013); compliance with this standard in the United States was required by January 2006 (Hilkert Colby et al. 2010).

Compliance with increasingly stringent standards for As in drinking water has led to expanded implementation of water-treatment

systems for As removal. This complements longer-term experience, for example in Chile, where full-scale treatment for As removal has been implemented since the 1970s (Sancha 2006). Ideally, this experience could serve as the basis to improve existing practices and to inform future implementation. Surveys and model-based mapping of the occurrence of geogenic As (Buschmann et al. 2008; Cremisini and Armiento 2016; Erban et al. 2014; O'Shea et al. 2007; Ravenscroft et al. 2009; Rodriguez-Lado et al. 2013; Rowland et al. 2011; Winkel et al. 2008) suggested that demand for water treatment for As removal is likely to increase. Although less common than geogenic sources, mining activities can also contribute to As contamination of source water used for drinking water in some locations, such as Chile (Cortina et al. 2016) and Thailand (Jones et al. 2008).

If future practice is to be guided by current experience with As removal at full scale, information on current practice must be both accessible and relevant to future application. For this paper, the authors sought information on current practice at full-scale to determine its potential benefit as a complement to the more-abundant and accessible information on bench-scale and pilot-scale studies. The availability of information from full-scale practice is discussed in the context of technology selection. Although this analysis focuses on centralized treatment [i.e., excluding point-of-use (POU) and point-of entry (POE) treatment] in high-income or upper-middle income countries, issues for low-income countries are considered (in the concluding section) in the context of the Sustainable Development Goal (SDG) 6 to "Ensure availability and sustainable management of water and sanitation for all" (United Nations 2016).

Assessing Treatment Options Based on Expected Performance and Cost

Assessment of available treatment options is needed both for the selection (i.e., by water suppliers) of the most-appropriate technology for a given application and also in the context of setting enforceable drinking water standards [e.g., a (primary) maximum contaminant level (MCL) in the United States]. Technical and economic feasibility were evaluated by the U.S. Environmental

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Protection Agency (U.S. EPA) for the 2001 revision of the As MCL and were also addressed in practice-oriented journals (Chen et al. 1999). Subsequent to adoption of the revised MCL, guidance on expected performance, suitability, and costs of As treatment technologies were provided, with an emphasis on small systems (i.e., those serving fewer than 10,000 persons) (U.S. EPA 2003). Operation and maintenance (O&M) and capital cost curves as a function of flow or number of households served were developed based on models for small systems, combined with field studies of performance, chemical cost estimates from manufacturers, and standard labor cost estimates (U.S. EPA 2000). Further demonstration studies were also conducted on small systems across the continental United States (U.S. EPA 2005).

The U.S. EPA guidance document for small systems provides a series of decision trees for technology selection (U.S. EPA 2003). Existing treatment processes (i.e., at a given facility) were identified as a key input for the decision based on the reasonable assumption that optimizing an existing treatment process would be more economical than installing a new treatment process. In general, conventional coagulation/filtration or lime-softening systems were not recommended for new installations solely for As removal. Although adsorption on granular ferric hydroxide (GFH) was identified as a promising technology, information on performance available at the time was insufficient to provide cost estimates. Further considerations for technology selection included waste generation and local constraints on waste disposal.

Factors affecting treatment performance and possibilities for treatment optimization are addressed in the extensive literature on bench-scale studies of As removal from drinking water, which has recently been reviewed (Davis and Edwards 2014; Jadhav et al. 2015; Mondal et al. 2013; Singh et al. 2015). Bench-scale studies are, however, less reliable than pilot-scale studies as a basis for establishing the suitability of a treatment process for a specific source water and environmental conditions and obtaining the data necessary for full-scale design (Crittenden et al. 2012). A key component of pilot-scale studies is the use of the same raw water (i.e., source water) to be treated in the eventual full-scale plant. Modification of influent water composition (e.g., spiking with As) can be included to examine the effect of the concentration of the target contaminant, as was done in a study of enhanced coagulation for As removal (Cheng et al. 1994). Although pilot studies cannot eliminate all potential effects of scale-up, they are recommended as a basis for optimizing operating parameters, avoiding failures, and improving cost estimates (U.S. EPA 2003). For process understanding and optimization, a useful variation on pilot-testing are studies that interrogate existing treatment processes by incorporating intensive water-quality sampling along the treatment train. This approach was used in an early study of As removal in treatment plants operating for iron (Fe) and manganese (Mn) removal, enhanced softening, or alum coagulation (McNeill and Edwards 1995) and to identify the factors affecting As(III) oxidation and removal concurrent with oxidation and removal of Fe, Mn, and ammonium (Katsoyiannis et al. 2008). Pilot testing can be particularly useful for evolving or novel technologies. In the case of coagulation combined with microfiltration rather than sand filtration, pilot testing demonstrated the feasibility of microfiltration using pH control to decrease the necessary coagulant dose (Chwirka et al. 2004; Ghurye et al. 2004). Pilot testing also identified pH as a key factor for process optimization in As removal by activated alumina and ion exchange (Hathaway and Rubel 1987). However, piloting is not consistently applied or useful across utilities; pilot testing in California systems implementing As removal technologies was not associated with improved prediction of performance (Hilkert Colby et al. 2010).

Treatment Technology Performance in Demonstration Studies and Routine Operation

Experience with full-scale treatment offers a more-realistic basis for performance assessment than bench studies or even pilot studies and, furthermore, allows for validation of estimated costs and performance. Demonstration studies were conducted in small systems across the United States between 2004 and 2010; all studies were conducted for at least 1 year, but in some cases, adaptations to the technologies or process conditions were made during the study (Gutierrez 2015; U.S. EPA 2005). The most commonly assessed technologies were adsorptive media (mainly alone but also in combination with Fe removal), concurrent As and Fe removal and coagulation/filtration. These studies are summarized in the on-line Supporting Information (Table S1) based on Final Reports available from the U.S. EPA (2016); the small number of studies ($n = 4$) using ion exchange or reverse osmosis (RO) were not included. The largest system included in the demonstration studies served a population of 8,300. Influent As concentrations generally ranged between 20 and 90 $\mu g/L$ with As occurring in both the +III and +V oxidations states. The demonstration studies generally focused on system reliability and performance, required O&M and operator skill levels, and capital and O&M costs. Some treatment processes or conditions were modified during the demonstration study to improve performance (Gutierrez 2015). For example, a system designed for Fe removal (Climax, Minnesota) failed to achieve adequate As removal and was modified for coagulation/filtration with addition of ferric chloride ($FeCl_3$). In a system employing Fe-based adsorptive media (Brown City, Michigan), a pre-chlorination step was added to control the steadily increasing As concentrations observed in the filter effluent, though this also resulted in increased backwash frequency. A valuable feature of the demonstration studies was the weekly sampling of influent and effluent water quality, which provided important insights into process reliability.

Performance in routine operation must be sufficient to comply with drinking-water standards. Utilities and/or water suppliers generally report raw and finished water quality to customers as well as to regulatory agencies. Some reporting of information on installed technologies is also required [e.g., as part of the U.S. EPA *Community water system survey* (U.S. EPA 2015)]. Regulatory agencies may also conduct targeted studies, such as the survey of performance and cost for As removal in selected systems conducted by the California Department of Public Health in 2008 (Hilkert Colby et al. 2010). Utilities, water-treatment plant managers, and/or system owners or operators also have a vested interest in assessing the performance of installed technologies to identify needs and opportunities for optimization or as the basis for future implementation decisions. Although these interests may not extend to making such information widely available, in some cases, information derived from utility experience may be reported in academic publications or professional newsletters.

In the following sections, information on installed technologies is provided by region, beginning with Latin America, which has the longest experience with arsenic removal from drinking water. This regional approach highlights the different priorities and challenges in various regions. Types of treatment processes are summarized, with an emphasis on larger systems. Comparisons of regional experiences are made in the following section.

Installed Treatment in Latin America

The longest experience with full-scale treatment for As removal from drinking water has been in northern Chile, where health

effects of As exposure were identified in the 1960s (Sancha 2006). Usually, this exposure resulted from elevated As concentrations in surface water (up to 900 μg/L) as well as in groundwater (up to 80 μg/L). Surface waters have been treated by pH adjustment with acid, pre-oxidation with chlorine, coagulation with $FeCl_3$, sedimentation, filtration, and final disinfection. For groundwater, the sedimentation step was omitted in some processes. Three plants were built in the 1970s with treatment capacities of about 40,000 m^3/day. A more-recent report (G. Ahumada Theoduloz, personal communication, 2016) identifies 12 treatment plants in operation with capacities of between 2,600 and nearly 90,000 m^3/day treating surface water and groundwater with influent As concentrations between 16 and 500 μg/L (Table 1). In addition to the processes used in the older treatment plants, As removal is also accomplished without coagulant addition (i.e., by filtration in an adsorbent bed using Bayoxide 33).

Treatment plants for As removal from drinking water are also in operation or under development in other countries in Latin America, particularly Argentina and Guatemala (Cortina et al. 2016). Treatment of Argentinian groundwater for As removal is complicated by elevated concentrations of silica and fluoride (F) and generally high mineral contents. To meet these challenges, RO is used in Santa Fe province, treating flows up to 2,400 m^3/day. Concurrent removal of As and F is accomplished by coagulation with polyaluminum chloride with a two-step filtration process. This process is installed in plants with capacities of 150–850 m^3/day. In Guatemala, coagulation-filtration is used to treat approximately 4,400 m^3/day of groundwater from two wells with an average As concentration of 150 μg/L (Garrido Hoyos et al. 2013). A coagulant dose of 12 mg/LFeCl$_3$ is used with sedimentation before filtration and disinfection. A ceramic filter medium is used to minimize color and Fe in the produced water. Although As contamination has been reported in some drinking-water supplies in Mexico, effective treatment has not yet been installed (Cortina et al. 2016).

Installed Treatment in Vietnam

The largest population served with drinking water treated to remove As is most probably the population of about 6 million people served by the Hanoi Water Works in Vietnam. Currently, 13 groundwater treatment facilities (ranging in size from 25,000 to 90,000 m^3/day with total production of 800,000 m^3/day) are in operation (DSI 2016). Due to high naturally-occurring Fe(II) concentrations [typically 3 to 15 mg/L (Le et al. 2007)], source water has been treated for Fe removal even before the discovery of elevated As concentrations. In the treatment facilities, groundwater is aerated, facilitating the oxidative precipitation of naturally-occurring Fe; precipitates are allowed to settle in a sedimentation basin and the effluent is passed through a sand filter and, finally, disinfected with chlorine. Removal of As (present in the source water at concentrations up to 350 μg/L) is accomplished by sorption/coprecipitation with Fe(hydr)oxides. Concentrations of As in the finished water are generally <30 μg/L but vary depending on Fe concentrations and the ratios of Fe-to-As (and phosphate) in the source water. Some further removal of As occurs in the distribution system as a result of As sorption onto Fe(hydr)oxide surfaces formed by corrosion of iron pipes (Berg et al. 2001).

Installed Treatment in Europe and the Middle East

In Greece, elevated As concentrations in groundwater are associated with geothermal activity or release from alluvial sediments. Water containing As (at concentrations generally below 50 but in one case up to 200 μg/L) is treated at eight treatment plants with capacities between 480 and 2,400 m^3/day (Katsoyiannis et al. 2015). Arsenic is present mainly as As(III). Preoxidation is usually accomplished by aeration (i.e., biological treatment). In one case, ozonation is used because Fe(II) and Mn(II) concentrations in oxic groundwater are too low to stimulate biological (Fe and/or Mn) oxidation. Preoxidation is required for this oxic groundwater because As(III) concentrations exceed the 10 μg/L standard even though As occurs predominantly in the +V oxidation state. Arsenic is removed by coagulation with ferric salts or adsorption onto Fe-based packed-bed media (Katsoyiannis et al. 2015). In addition to the adsorbents that rely solely on Fe (i.e., GFH and Bayoxide), a mixed Fe- and Mn oxide (AquAsZero) is used that can oxidize As (III) in addition to adsorbing As (Tresintsi et al. 2013a).

In Italy, elevated As concentrations (up to 100 μg/L) occur in groundwater across the northern provinces, with concentrations of up to 500 μg/L reported further south in the province of Campania. A survey of 19 (unidentified) treatment plants across Italy (Sorlini et al. 2014) reported that 10 plants, including those handling the highest flows (up to 39,000 m^3/day), used chemical precipitation (i.e., coagulation) with $FeCl_3$. Chemical precipitation was combined with adsorption on GFH in two plants and GFH was used alone or with preoxidation in four plants. Titanium dioxide was used as an adsorbent in two plants but only with low (52 m^3/day) or unreported flows. Use of RO was reported for two plants (in one, as a polishing step after GFH) and use of ion exchange was reported in one plant. Aeration combined with biofiltration or other preoxidation was used in all but five systems; in these five systems, two used adsorption on GFH, one used adsorption on titanium dioxide, one used RO, and one used ion exchange. In the central province of Lazio, As occurred at concentrations up to 30 μg/L in communal water supplies in 2004; by 2013, values below 10 μg/L were reached throughout the region treating flows up to 31,000 m^3/day (Aqualatina 2017) by adsorption on GFH (C. Bahr, personal communication, 2016).

Elevated As concentrations in artesian groundwater occur widely in the Pannonian basin in east-central Europe (e.g., in the countries of Hungary, Serbia, and Croatia) (Habuda-Stanic et al. 2007; Jones et al. 2008; Sipos et al. 2010; Tubic et al. 2010). Installed treatment includes conventional biofiltration (for removal of Fe, Mn, and ammonium) (Sipos et al. 2010), coagulation-filtration, and direct filtration (Habuda-Stanic et al. 2007). Even though the Croatian coagulation-filtration plants achieve 85% removal of As, the treated water still contains 40 μg/L As; biofiltration plants are also unable to meet the 10 μg/L standard.

In Iran, As is also removed from drinking water by adsorption onto GFH. The adsorbent is installed in five treatment lines with a total capacity of 10,800 m^3/day; the influent As concentration is 145 μg/L (F. Tarah and M. Mahdyarfar, personal communication, 2016).

Installed Treatment in the United States

The change in the As MCL had significant consequences for groundwater-based public drinking water supplies in California. In January 2009, 145 systems (mainly small systems) were out of compliance with the revised As MCL and about 60 systems had installed treatment systems for As removal (Hilkert Colby et al. 2010). About half of the systems with installed treatment were surveyed by the California Department of Public Health; of these, 15 used adsorption processes, 6 used ion exchange to treat average flows up to about 10,400 m^3/day, and 15 used coagulation/filtration (or oxidation/filtration) to treat average flows up to about 24,000 m^3/day. Average influent As concentrations were generally

Table 1. List of Treatment Plants Operating for Arsenic Removal in Chile

Service	Company	Plant[a]	Water source	Other contaminants	Flow (m³/day)	Influent As (μg/L)	Treatment process	Wastewater-treatment process
Arica	Aguas del Altiplano	Pago de Gómez	Groundwater	—	13,000	18	Filtration through adsorbent bed—reverse osmosis	No water discharge
Iquique-Alto Hospicio	Aguas del Altiplano	Santa Rosa	Groundwater	—	20,700 (13,400)	60–80	Oxidation—direct filtration—ultrafiltration	Coagulation—flocculation—sedimentation—filtration-thickener—centrifugation
Iquique-Alto Hospicio	Aguas del Altiplano	El Carmelo	Groundwater	—	65,000	16	Oxidation—direct filtration	Coagulation—flocculation—sedimentation—filtration—thickener—centrifugation
Pozo Almonte	Aguas del Altiplano	Pozo Almonte	Groundwater	Sulfates	2,900	16	Reverse osmosis	Discharge to a sewage treatment plant
Calama	Aguas Antofagasta	Cerro Topater	Surface water	Turbidity	43,000	400–450	Oxidation—coagulation—flocculation—sedimentation—filtration	Thickener—centrifugation
Antofagasta	Aguas Antofagasta	Salar del Carmen	Surface water	Turbidity	86,000	400–450	Oxidation—coagulation—flocculation—sedimentation—filtration	Thickener—centrifugation
Taltal	Aguas Antofagasta	Taltal	Groundwater	—	2,600	60–80	Oxidation—direct filtration	Discharge to a sewage treatment plant
Diego de Almagro	Aguas Chañar	Diego de Almagro	Surface water	Turbidity, chloride, total dissolved solids, sulfates	3,000	100–500	Oxidation—filtration—reverse osmosis	Without treatment
Santiago Oriente	Aguas Cordillera	Lo Gallo[b]	Surface water and groundwater	Turbidity iron, manganese	56,000	10–50	Oxidation—coagulation—flocculation—sedimentation—filtration	Discharge to a river without treatment
Santiago Oriente	Aguas Cordillera	San Antonio	Groundwater	—	43,000	17–34	Oxidation—filtration—filtration through adsorbent bed	Coagulation—flocculation—sedimentation—thickener—press filter
Lampa	Aguas Manquehue	Alto Lampa	Groundwater	—	4,300	20	Oxidation—filtration through adsorbent bed	No water discharge
Santiago (Quilicura)	Aguas Andinas	Quilicura	Groundwater	—	8,600	60	Oxidation—filtration through adsorbent bed	No water discharge
Santiago (Colina)	Aguas Manquehue	Lo Pinto	Groundwater	—	10,400	25	Oxidation—filtration through adsorbent bed	No water discharge
Rancagua	ESSBIO	Nogales[b]	Surface water	Turbidity	65,000	20	Oxidation—coagulation—flocculation—sedimentation—filtration	Discharge to a river without treatment

[a]All plants are in operation except El Carmelo (Aguas del Altiplano) and San Antonio (Aguas Cordillera) (which are under construction); the Santa Rosa plant is being expanded.
[b]These plants were initially constructed for turbidity removal and later upgraded to remove arsenic.

below about 50 μg/L for the adsorption systems (with one very small system treating water with an influent As concentration of 180 μg/L), below 35 μg/L for coagulation/filtration systems, and below 22 μg/L for the ion exchange systems.

The City of Los Angeles, California, is one of the very few large systems with elevated As concentrations (up to approximately 60 μg/L) in a surface source water (Kneebone and Hering 2000). Arsenic inputs derive from geothermal sources in the Owens Valley (Wilkie and Hering 1998). As an interim measure, As is removed by addition of FeCl$_3$ just upstream of Haiwee Reservoir in Olancha, California (Kneebone et al. 2002); sludge from this process accumulates in the reservoir, allowing the treated water to be transported through the Los Angeles Aqueduct (LAA) to a direct filtration plant in Sylmar, California. Drinking water supplied over 4 million inhabitants in the City of Los Angeles meets the As MCL of 10 μg/L. In order to eliminate the need for the current interim treatment, upgrading the LAA Filtration Plant by adding enhanced coagulation was planned for 2021 (LADWP 2011) but has been postponed to 2032 (LADWP 2015).

Albuquerque, New Mexico, was identified before the revision of the As MCL as one of the few large systems that would need to install treatment to comply with the revised standard (Chwirka et al. 2000). After pilot-testing (Chwirka et al. 2004), a coagulation/microfiltration demonstration plant with a capacity of about 20,000 m^3/day was completed in 2007 (ABCWUA 2016). A combination of selective pumping, blending, and groundwater treatment for As removal is used to supply drinking water that meets the As MCL.

Comparison of Regional Experiences with Installed Treatment

Treatment processes for As removal are currently installed at drinking-water treatments worldwide. The most commonly-used treatment processes are coagulation (with ferric salts, also called chemical precipitation) combined with filtration and adsorption on (usually) Fe-based media. Comparing and contrasting experiences from full-scale treatment plants in different regions allows the identification of some key factors influencing performance.

Coagulation/Filtration

Coagulation/filtration is most commonly used for larger-capacity facilities (up to 90,000 m^3/day) and, based on Chilean experience, is recommended for flows exceeding 2,600 m^3/day (Cortina et al. 2016). When the upgrade of the LAA Filtration Plant is completed, this facility (which treats 2.6 Mm^3/day) will be more than an order of magnitude larger than any existing facility. Options for improving the performance (i.e., As removal) of coagulation/filtration plants include adjusting pH and coagulant dose. In Chilean plants, FeCl$_3$ doses up to 56 mg/L have been used with H$_2$SO$_4$ added for pH adjustment (Sancha 2006). In California, however, most of the coagulation/filtration systems surveyed reported not using pH adjustment (Hilkert Colby et al. 2010). In Italy, plants treating source waters with As concentrations above 40 μg/L either added coagulant (3–7 mg/L as FeCL$_3$) in two steps or combined coagulant addition (i.e., chemical precipitation) with adsorption on GFH (Sorlini et al. 2014). In Greek treatment facilities using coagulation/filtration, capacity has been reported to be limited by passage of Fe through the filters at linear velocities exceeding 8 m/h; use of organic polyelectrolytes to increase the floc size and enable more-efficient particle filtration at higher linear velocities is under consideration (M. Mitrakas, personal communication, 2016). This is consistent with observations in bench-scale studies (Zouboulis

and Katsoyiannis 2002). When drinking-water standards are met, the efficiency of As removal is often not reported. There are a few exceptions in literature published by academic authors. For example, 80–100% removal of As(V) was reported for Chilean treatment plants (Cortina et al. 2016). An efficiency of 80% As removal based on measurements after sand filtration was reported for a full-scale plant that serves the city of Cremona in northern Italy (with a capacity of 38,400 m^3/day). This plant uses aeration, biological filtration, addition of KMnO$_4$ as an oxidant and FeCl$_3$ as a coagulant, sand filtration, and disinfection; Mn and ammonia were efficiently removed (>95%) in the biological filtration step (Sorlini and Gialdini 2014).

Disposal of waste (i.e., As-containing sludge or backwash solids) from such processes may increase costs if on-site disposal or direct sewer discharge is not possible (Sullivan et al. 2010). In the California survey, only one system reported using off-site disposal (though five systems did not report on waste disposal) (Hilkert Colby et al. 2010). In Italian treatment plants using coagulation (i.e., chemical precipitation), backwashing frequency [both for the biological filters and secondary (i.e., postchemical addition) filters] varied between three times per day and three times per week (Sorlini et al. 2014). Backwash water was generally discharged to the sewer system, though in one of the smaller plants (capacity 260 m^3/day) sludge thickening and/or dewatering was performed. In Chilean plants, sludge containing up to 30 kg As was reported to be generated each day (Cortina et al. 2016). Treatment of wastewater generated by Chilean plants is highly variable; however, sedimentation, thickening, and dewatering are incorporated in most plants using coagulation/filtration that were built in the last decade (Table 1).

In the Hanoi drinking-water-treatment facilities, the As removal process relies on naturally-occurring Fe in the source water, eliminating the need for coagulant addition (DSI 2016); sedimentation is still used to remove sludge prior to filtration. Direct filtration (i.e., avoiding the need for a sedimentation basin) has been used in Chile to treat groundwater with As <100 μg/L at 2,800 m^3/day (Sancha 2006) as well as in Greece (Katsoyiannis et al. 2015). The sedimentation step is also omitted in the coagulation/microfiltration system used in Albuquerque, NM [Albuquerque Bernalillo County Water Utility Authority (ABCWUA 2016)].

Adsorptive Media

Adsorptive media (mainly Fe-based) is more often applied in lower-capacity systems though there is considerable overlap in the capacity of adsorption and coagulation/filtration systems. For smaller systems, the lower efficiency of As removal on an As:Fe basis for adsorption as compared with coagulation (Tresintsi et al. 2013b) is offset by ease of operation of adsorption systems, which do not require separate settling and/or filtration steps. One major cost associated with adsorptive media is replacement of the adsorbent after exhaustion. In the California systems surveyed and also in some of the U.S. EPA demonstration studies, breakthrough occurred before the expected run length. These discrepancies might be attributable to variations in water quality, especially in the concentrations of silica and vanadium (Hilkert Colby et al. 2010). The basis for the estimated capacity, however, is rarely specified by the manufacturer or service provider. One California utility reported substantial cost savings achieved by regeneration of Fe-based media (as opposed to disposal after single use as usually recommended by suppliers); the use of corrosive chemicals for regeneration, however, requires adequate safety precautions and operator training (Westerling 2014).

Preoxidation

Preoxidation (i.e., before As removal) can significantly improve treatment performance if As is present in the source water as As(III) (i.e., arsenite). In Vietnam, most of the As(III) is oxidized by cooxidation with Fe(II) during aeration (DSI 2016) and, in Greece, by biological oxidation stimulated by oxygenation (Katsoyiannis et al. 2015). In one example of a private Greek treatment plant, however, biological oxidation was not stimulated despite the presence of 10 mg/L Fe(II) and 2 mg/L Mn(II); neither Mn(II) or As(III) was oxidized and As concentrations in the source water (40 μg/L) were not sufficiently decreased to meet the 10 μg/L standard (I. Katsoyiannis, personal communication, 2016). A problem with incomplete As(III) oxidation at the Mitrousi plant in Greece also occurred when an attempt was made to increase capacity (i.e., flow rate) without upgrading the oxygen generator (M. Mitrakas, personal communication, 2016).

Although aeration is generally quite economical, it is not always sufficient; preoxidation can add significantly to costs if chemical oxidants are used. In the Greek village of Triglia, Fe(II), Mn(II) and ammonium concentrations are insufficient to support biological oxidation and ozone is used to oxidize As(III) (Katsoyiannis et al. 2015). In Chile, although As occurs mainly in the +V oxidation state, As(III) concentrations are high enough to require preoxidation, usually with chlorine though permanganate is also used (G. Ahumada Theoduloz, personal communication, 2016). Tests of chemical oxidants conducted at the As removal facilities in Vietnam indicated that the high ammonium levels in the groundwater would pose problems associated with chloramine formation if chlorine were used as a oxidant in place of aeration (Le et al. 2007).

Some treatment processes for As removal, particularly ion exchange or sorption on aluminum-based adsorptive media, are not effective for As(III) (Bissen and Frimmel 2003; Chen et al. 1999). Treatment process such as Mn greensand filtration or sorption on Mn(IV)-based adsorptive media can promote in situ As(III) oxidation (Driehaus et al. 1995). Suppliers of Fe-based adsorptive media claim effective removal of both As(III) and As(V) (AdVantEdge 2011). In a demonstration study treating As(III)-containing groundwater in Queen Anne's County, Maryland, however, prechlorination was implemented after the treatment system using the Fe-based adsorptive media SORB 33 exhibited unacceptably early breakthrough of As (Chen et al. 2008). In Chilean experience with coagulation using $FeCl_3$, efficiencies of As(III) removal were only 40–70%; substantially higher removal efficiencies (80–100%) were achieved for As(V) (Cortina et al. 2016).

Co-Occurring Contaminants

Additional complications arise when As-containing source waters also contain other, co-occurring contaminants or even otherwise unproblematic constituents of source waters such as silicate (Meng et al. 2000) or phosphate (Katsoyiannis et al. 2004). In some locations in Argentina, for example, RO was selected for As removal, despite the high costs and water wastage, so that the high TDS (total dissolved solids) in the source water could be treated simultaneously (Cortina et al. 2016). Ion exchange has been recommended for concurrent removal of As and nitrate (Ghurye et al. 1999) although it can be subject to chromatographic peaking, which can release contaminants in excess of their influent concentration (Clifford et al. 2011). Co-occurrence of As and F in Italy was managed by treating source waters in parallel by RO (for F) and adsorption on GFH (for As) and recombining the produced water from each treatment train (Sorlini et al. 2014). Co-occurrence

of As and antimony (Sb) in Melivoia (Greece) resulted in the abandonment of a treatment plant using adsorption on the Fe-based medium Bayoxide for As removal (Katsoyiannis et al. 2015). Although As was efficiently removed, Sb (present at 20 μg/L) exhibited rapid breakthrough above the European Union drinking water standard of 5 μg/L. This rapid breakthrough was consistent with the demonstrated inefficiency of Sb(V) removal by coagulation with ferric salts (Guo et al. 2009). The occurrence of uranium (U) as a co-contaminant with As can lead to complications in the disposal of spent Fe-based adsorptive media; pretreatment (e.g., by ion exchange) to remove U before use of Fe-based media for As removal is recommended if there is a potential for U accumulation (SVGW 2015).

Issues Identified through the Comparison of Regional Experiences

Comparison of experiences gained through full-scale implementation of As removal provides some insight into the issues that have arisen in practice as well as needs for improvements and open questions. For example, the efficiency of precipitate and/or floc removal by filtration limits the effectiveness of As removal in several systems. The effectiveness of As(III) oxidation without the addition of chemical oxidants exhibits considerable variability, which is not adequately explained in some cases. Although oxygen alone is not effective in oxidizing As(III), this process can be biologically mediated or occur in conjunction with Fe(II) oxidation (Hug and Leupin 2003). The system design [e.g., residence time in biological filters or influent Fe(II) concentrations] will influence whether adequate As(III) oxidation is achieved. The presence of co-occurring contaminants substantially increases the difficulty of achieving adequate As removal; treatment optimization under these conditions would benefit from a better exchange of experience and from studies that would address the underlying physical-chemical phenomena.

Addressing Inadequacies in the Availability of Information on Installed Treatment

Despite the potential benefits associated with sharing information on installed treatment technologies, the quality and accessibility of this information is very variable. The U.S. EPA conducted surveys of community water systems (CWS) in 1995 2000, and 2006. In the 2006 survey, only 4% of systems reported treating water for removal of inorganic chemicals (U.S. EPA 2009). Arsenic, although it would be included in the category of inorganic chemicals, was not listed as a contaminant in the accompanying database. Since this survey has not been repeated since compliance with the 10 μg/L As standard has been required, information on installed treatment for As removal in the United States is not available through any central source. For other countries, even the CWS survey framework appears to be absent. Nonetheless, information access through regulatory agencies (e.g., U.S. EPA) provides an objective (even if not always up-to-date) source of information on treatment technologies.

Additional relevant information access is provided through websites hosted by chemical manufacturers, consulting firms and professional associations. Some examples are listed in the supporting information (Table S2). The potential benefits of such resources are, however, compromised by the proliferation of competing websites as well as issues related to paywalls, possible biases, and quality control.

Potential Benefits of Improved Access to Information on Installed Treatment

With the rapid advances in information technology, the technical barriers to sharing information and knowledge are shrinking. An international, accessible database or even a metadata portal for installed technologies for As removal [which could be operated as an open (i.e., wiki) platform] offers the potential to benefit from past and ongoing experience in practice. Ideally, information on the performance of treatment plants would be available online; a path-breaking example of real-time performance data is provided for coagulation-flocculation-sedimentation plants operated for turbidity removal in Honduras (Agua Clara 2016). Such platforms would be fully consistent with the aims and goals of the Technology Facilitation Mechanism (United Nations 2017), which is part of the efforts of the United Nations (UN) to support the Sustainable Development Goals, or of the Water Solutions Lab Network, which is being developed by the Sustainable Water Future Programme (SWFP 2017) in cooperation with Future Earth (2017).

A database on installed treatment technologies [including relevant data on influent water quality, flow and (where available) performance] could also make it possible to embed pilot or demonstration studies in existing treatment-plant operations. Required water quality reporting (e.g., Consumer Confidence Reports in the United States), which are based on annual average values, do not provide sufficient information to understand factors that affect the performance of treatment systems. This could be addressed through embedded demonstration studies incorporating more-intensive sampling of influent and effluent water quality. Embedded pilot studies could be conducted either for optimization of installed technologies or testing of alternatives, not only for the facility hosting the embedded pilot study but also for other systems facing comparable challenges. Both of these activities would benefit from cooperation among system owners and operators, academics and consultants.

The sharing of experience gained through embedded demonstration and/or pilot studies could have substantial humanitarian benefits as communities and agencies seek to meet the Sustainable Development Goal (SDG) 6 ("Ensure availability and sustainable management of water and sanitation for all"). Target 6.1 calls for achieving "universal and equitable access to safe and affordable drinking water" by 2030; the suggested indicator for this goal explicitly includes priority chemical contaminants (United Nations Water 2016). For developing countries, greater reliance for the provision of drinking water with <10 μg/L As will likely be placed on household (i.e., POU) treatment. Although the effectiveness of many such technologies has been demonstrated, POU treatment also imposes significant responsibilities on the user and require that maintenance and waste disposal issues are dealt with appropriately (Jain and Singh 2012; Malik et al. 2009; Yadav et al. 2011). In recognition of the challenges posed by household treatment, international efforts have been directed toward providing accessible and reliable information on available technologies and their implementation through organizational websites (WHO 2016) and web-based toolkits (Conradin et al. 2010), and manuals (Eawag 2015). Comparable efforts to expand the access to information on centralized treatment processes, as called for in this paper, would reflect the fact that the SDGs also apply to industrialized (high-income and middle-income) countries.

Acknowledgments

Supplemental Data

Tables S1 and S2 are available online in the ASCE Library (www.ascelibrary.org).

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