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National primary drinking water regulation for arsenic: A retrospective assessment of costs

Abstract: This paper compares EPA's ex ante cost analysis of the 2001 maximum contaminant limit (MCL) for Arsenic in Drinking Water to an ex post assessment of the costs. Because comprehensive cost information for installed treatment technologies or other mitigation strategies pursued by water systems to meet the new standard is not available, this case study relies upon ex post cost data from EPA Demonstration Projects, capturing a total of 50 systems across the US. Information shared by several states and independent associations on the types (but not costs) of treatment technologies used by systems is also summarized. Comparisons of predicted costs to realized costs using our limited data yield mixed results. Plotting the capital cost data from the Demonstration Projects against the cost curves for the compliance technologies recommended for smaller systems, we find that the EPA methodology overestimated capital costs in most cases, especially as the size of the system increases (as measured by the design flow rate).

Keywords: cost analysis; drinking water regulation; regulatory costs; retrospective study.

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1 Introduction

On January 22, 2001, EPA published new National primary drinking water regulations for arsenic (the "Arsenic Rule"). The Arsenic Rule lowered the maximum contaminant level (MCL) for arsenic in drinking water from 50 micrograms/liter (µg/L) to 10 µg/L. The rule applied to 54,000 community water systems (CWSs) and 20,000 other systems known as non-transient non-community water systems

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(NTNCWSs) that serve non-residential communities (e.g., schools, churches). Water systems had to comply with this standard by January 23, 2006. EPA estimated that approximately 3000 CWSs and 1100 NTNCWSs would need to treat their drinking water to meet the 10 μg/L standard. Of those systems affected, 97% were considered "small systems" serving 10,000 people or fewer.

The Arsenic Rule was particularly important in that it was the second drinking water rule in which EPA used the discretionary authority afforded by §1412(b)(6) of the Safe Drinking Water Act to adjust the MCL to a level above that which is technically feasible if the benefits do not justify the costs. While the Agency initially proposed an MCL for arsenic of 5 μg/L, EPA ultimately set the drinking water standard at 10 μg/L, concluding that the MCL of 10 μg/L maximized health risk reduction at a cost justified by the benefits (US EPA, 2000a). The technically feasible level for arsenic removal from water was established at 3 μg/L.

The costs associated with the Arsenic Rule include: 1) the costs of water systems to comply with the standard which includes treatment costs, monitoring costs and administrative costs of compliance and 2) the costs to States to implement and enforce the rule. The total annual costs of the rule were estimated to be approximately $181 million (1999$), with treatment costs comprising the bulk at about $171 million. The total costs to CWSs were approximately $172 million while the costs to NTNCWSs were estimated to be $8.1 million. EPA also estimated total annual treatment costs by system size across CWS and for NTNCWSs, by NTNCWS system service type.[1]

The cost implications for households were dependent on the size of their CWS. For households served by small CWSs (those serving fewer than 10,000 people), the annual increase in cost was expected to range between $38 and $327. For those served by CWSs that serve >10,000 people, the estimated annual household costs for water were expected to increase from $0.86 to $32. The disparity in household costs between systems sizes was due to economies of scale, with larger systems able to spread the costs they would incur over a larger customer base.

The purpose of this paper is to examine how EPA's ex ante cost analysis of the Arsenic Rule compares to an ex post assessment of costs. This is not an evaluation of how well EPA conducted the ex ante analysis at the time of the rulemaking, but

1 EPA also estimated the health benefits associated with reductions in arsenic concentrations. Based on the available science at the time, EPA quantified and monetized expected reductions in bladder and lung cancers with estimates ranging from $140 to $198 million (1999$). However, a number of health outcomes associated with arsenic exposure remained unquantified, including cancers of the kidney, skin, and prostate, endocrine disorders (e.g., diabetes) and other cardiovascular, pulmonary, and neurological effects. We do not conduct an ex post assessment of benefits to compare to these ex ante benefit estimates.

rather it is to see if we can gather enough information on the key drivers of compliance costs to make an informed *judgment* as to whether ex post costs are higher or lower than the estimates of ex ante costs for this rule. We are interested to see if actual costs diverged from ex ante costs and, if so, what factors caused this divergence (e.g., changing market conditions, technological innovation, etc.).[2]

While EPA used sound science and the best available information to estimate the costs associated with the rule in its benefit-cost analysis, there are several reasons why ex ante costs may differ from ex post costs. For example, technological innovation or regulatory or technical constraints could result in water systems using different treatment technologies for arsenic removal than assumed by EPA. The heterogeneity of water systems affected by the new arsenic standard introduces uncertainty into the ex ante cost estimates because EPA had to make assumptions about the type and size of systems that would exceed the standard as well as the treatment technologies those systems would use to reduce arsenic levels. The ex post data are extremely limited as well. These factors all add to the analytic challenges of how to determine and evaluate the costs faced by water systems affected by the Arsenic Rule.

The remainder of the paper is organized as follows: Section 2 summarizes the methods EPA used to produce ex ante compliance costs for the final rule by water system type and size (number of people served). Section 3 describes sources of information available to conduct an ex post cost assessment of the Arsenic Rule followed by our ex post cost assessment in Section 4. Section 5 presents a very limited comparison of ex ante and ex post compliance costs using data from a narrow set of demonstration projects designed to show the effectiveness of various treatment technologies at reducing arsenic levels. And the last section, Section 6, summarizes the analytic challenges we faced in conducting an ex post cost assessment of this rule.

2 Ex ante compliance cost prediction methodology

2.1 Identification of best available treatment technologies

EPA's ex ante compliance cost estimates for the Arsenic Rule required the identification of the "best available technologies" (BAT) effective at removing arsenic

2 For a broader discussion of reasons why ex ante and ex post costs may differ as well as more details on the development of the conceptual framework applied to this case study and ex post prediction strategies considered, please see Kopits et al., 2014.

and bringing water systems into compliance with the MCL. The following technologies were identified by EPA as BAT:
- Modified lime softening
- Modified coagulation/filtration
- Ion exchange
- Coagulation assisted microfiltration
- Oxidation filtration (greensand)
- Activated alumina

In addition to these centralized treatment technologies, EPA identified point-of-use (POU) devices as appropriate for small systems to achieve compliance with the arsenic MCL. POU involves treatment at the tap such as a water fountain or kitchen sink. The POU treatment options considered were:
- POU reverse osmosis
- POU activated alumina

Cost equations and the resulting cost curves for both capital and operating and maintenance (O&M) costs for each of these technologies are presented in the *Technologies and Costs for Removal of Arsenic from Drinking Water* (US EPA, 2000c) and serve as major inputs to EPA's prediction of compliance costs. Some of these technologies generate wastes that require disposal or pre-treatment (e.g., pre-oxidation or corrosion control) in order to be effective. Waste disposal capital and O&M cost curves were also presented for those technologies and included in the total costs of the BATs when relevant. The capital cost curves are a function of the system design flow (mgd, million gallons per day) while O&M cost curves are a function of the average flow (mgd) of the system. Alternative technologies such as sulfur-modified iron, iron filings, iron oxide coated sand, and granular ferric hydroxide still in the experimental stages are also discussed.

2.2 Main components of ex ante compliance costs

EPA employed different methods to estimate compliance costs for each of three different system categories: CWSs serving fewer than 1,000,000 people, NTNCWSs, and CWSs serving 1,000,000 people or more. In the economic analysis, EPA used a Monte Carlo simulation model (the Safewater XL model) to estimate compliance costs for the CWSs serving 1,000,000 or fewer people and a deterministic spreadsheet analysis to determine compliance costs for the NTNCWSs. EPA estimated compliance costs individually for the large systems (those serving 1,000,000 people or more) expected to exceed the standard. Total national compliance costs were then calculated by summing the compliance costs for the three system categories. Each methodology is discussed in more detail below.

Community water systems (systems serving <1,000,000 people). To estimate compliance costs for this size category of CWSs, EPA used the Safewater XL model. The model uses a combination of individual system data and distributional data (e.g., arsenic occurrence, number of entry points per system) to estimate costs. The data required for Safewater XL include a list of all water systems, system source type (groundwater or surface water), population served by the system grouped into one of eight size categories (<100; 101–500; 501–1000; 1100–3300; 3301–10,000; 10,001–50,000; 50,001–100,000; 100,001–1,000,000), and flow rate of the system. These data are available from EPA's safe drinking water information system (SDWIS) which contains data on all public water systems as reported by States and EPA Regions.

EPA estimated the number of entry points for each water system and its corresponding population size category using data from the 1995 Community Water Supply Survey.[3] Arsenic occurrence data are based on EPA's "Arsenic Occurrence in Public Drinking Water Supplies" report (US EPA, 2000b). Mean arsenic distributions for each system were estimated by sampling from observed data for actual systems with the same water source type in eight geographic regions of the country. Each system was assigned a random concentration from the arsenic occurrence distribution. The arsenic concentration for each system was then distributed (preserving the assumed mean) across each of the entry points in the system so that each entry point had its own assumed arsenic concentration.

The Safewater XL model then compared the arsenic concentration at each entry point to the 10 μg/L MCL standard. Entry points with predicted arsenic concentrations above the MCL were assumed to reduce the site concentration to 80% of the MCL, while entry points with predicted arsenic concentrations below the MCL were assumed not to employ any treatment.[4] For those entry points that required treatment, the Safewater XL model used a decision tree to assign a treatment technology to the entry point appropriate for the size and type of system.[5] Each decision tree assigned a probability to the application of a specific

3 Entry points are points at which water enters a water system's distribution network from wells, storage tanks or water treatment plants; in general, groundwater systems have more entry points than surface water systems and larger systems have more entry points than smaller systems.

4 Safewater XL calculates the percent reduction in arsenic concentration required to reduce the site concentration to 80% of the MCL standard (this is a safety factor that includes a 20% excess removal to account for system over-design).

5 EPA created sixteen decision trees: two source types for each of the eight group sizes.

treatment technology at a given entry point, with the probability dependent on the source water type, population size, and effectiveness across options based on the amount of arsenic requiring mitigation. Using the design flow and average flow of the system and the cost curves and equations developed in the *Technologies and Costs for Removal of Arsenic from Drinking Water* (US EPA, 2000c), capital and O&M costs at the site level were calculated for each treatment technology. A system's compliance cost was then determined by summing across the treated entry points in the system. By performing this analysis for each system expected to violate the MCL, EPA calculated a national estimate of compliance costs for CWSs.

Non-transient non-community water systems. For the NTNCWSs, EPA estimated compliance costs using a deterministic spreadsheet rather than the Safewater XL model. Similar to the methodology employed for the CWSs described above, the spreadsheet relied on the SDWIS data for information on the number of systems affected and the population served and used the same arsenic occurrence distribution developed above. Based on the design flow of the system, one of two treatment technologies was selected: (1) point of entry activated alumina or (2) centralized activated alumina. Point of entry activated alumina was selected for NTNCWSs with design flows <2000 gallons per day and the centralized active alumina was selected for all other systems. Capital and O&M costs were calculated based on the treatment technology selected and the design and average flow of the NTNCWS.

Community water systems (systems serving populations of 1,000,000 or more). For each of the nation's 25 largest drinking water systems – those serving 1,000,000 people or more, EPA developed individual compliance cost estimates using system specific information including entry point water quality parameters, system layouts, design and average flow, and treatment facility diagrams.[6] The resulting estimates were sent to each of the utilities for review and approximately 30% submitted revised cost estimates or additional arsenic occurrence data. EPA revised the cost estimates for those systems using these additional data. Of the 25 drinking water systems, three were expected to exceed the arsenic MCL – those located in Houston, Los Angeles and Phoenix. The cost estimates developed for these three systems accounted for approximately 20–25% of the total compliance costs estimated for the Arsenic Rule.

6 Some sources of these data included the Information Collection Rule, the community water systems survey, the association of metropolitan water agencies survey, the safe drinking water information system, the American water works association WATERSTATS Survey as well as discussions with system operators.

2.3 Main sources of uncertainty in ex ante cost estimates

Ex ante analyses are subject to many challenges and uncertainties. Selection of the most effective mitigation strategy depends on conditions that are specific to each system. Source of water (e.g., groundwater versus surface water), size of system (population served), and water quality conditions vary across systems. Water quality parameters such as pH, iron, sulfate and even the type of arsenic have implications for the effectiveness of a given treatment technology. However, EPA lacked information on exactly which systems would be out of compliance with the new MCL and relied on modeled outcomes. EPA based its cost estimates for these systems on predicted mitigation strategies. Over 90% of compliance costs were derived from a regulatory cost model, SafeWater XL. Modeled outcomes by design introduce uncertainty.

Location may also affect the choice of mitigation strategy. Proximity to other neighboring water systems or other alternative sources of water may favor blending or finding a new source. Further, waste streams containing arsenic resulting from the use of some technologies may be considered hazardous waste and subject to disposal regulations[7], with some states imposing their own requirements in addition to federal regulations. These waste disposal restrictions may further constrain the choice of technologies and ultimately affect the associated costs. In addition, some states may require pilot testing before the installation of a treatment technology, increasing the costs of compliance with the new MCL (US EPA, 2005). Technological innovation or regulatory or technical constraints could result in water systems using different treatment technologies for arsenic removal than the BATs listed by EPA. The SafeWater XL Model is not able to capture these potential exogenous factors that may influence how a water system will reduce their arsenic concentration.

3 Data and literature available to conduct ex post evaluation

3.1 Ex post literature

Prior to and after promulgation of the Arsenic Rule, a number of studies reviewing EPA's ex ante cost estimates were prepared – some in general support of the

7 See http://nepis.epa.gov/Adobe/PDF/20017IDW.pdf.

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Agency's estimates (e.g., Gurian, 2006; NDWAC 2001) and others contesting them (e.g., Bitner, Thomson, & Chwirka, 2001; Frey, Chwirka, Narasimhan, Kommineni, & Chowdhury, 2000). Because of the importance of the Arsenic Rule and the national debate surrounding it related to science and costs, EPA's Administrator publicly announced on March 20, 2001, that the Agency would take additional steps to reassess the scientific and cost issues associated with the Arsenic Rule. As part of that review, the Agency worked with its National drinking water advisory council (NDWAC) to review the assumptions and methodologies underlying the Agency's estimated costs for arsenic compliance. Upon finishing their review, NDWAC concluded that EPA "produced a credible estimate of the cost of arsenic compliance given the constraints of present rulemaking, data gathering, and cost models" (NDWAC 2001). In spite of the interest the Arsenic Rule generated at the time, our search of the literature identified only two studies that have made comparisons of ex ante and ex post costs of compliance with the Arsenic Rule: Gurian, Bucciarelli-Tieger, Chew, Martinez, & Woocay (2006) and Hilkert Colby, Young, Green, & Darby (2010).

Gurian et al. (2006) presents some limited comparisons of EPA's ex ante cost estimates and realized, ex post cost estimates for the Arsenic Rule using information from twelve EPA demonstration projects reported in Chen, Wang, Oxenham, & Condit (2004). Plotting the realized capital costs for these projects against EPA's cost curves for ion exchange and activated alumina, they find that, in 10 out of 12 cases, capital costs for the demonstration projects fell below the 1999 estimates. However, Gurian et al. caveat their results by noting potential biases embedded in the demonstration project cost estimates (e.g., biased vendor bids, tendency toward treatment technologies rather than non-treatment solutions, availability of additional expertise in devising a solution, etc.).

Gurian et al. also present the results of a small survey of six "large" water systems conducted in 2003 in which they ask about the progress each has made in coming into compliance with the new arsenic MCL.[8] Rather than compare these realized costs with EPA ex ante estimates, however, they make comparisons with pre-regulatory estimates derived and presented for these same six systems in Frey et al. (2000).

Hilkert Colby et al. (2010) perform a somewhat more comprehensive comparison of ex ante and ex post costs in their paper looking at costs of arsenic mitigation for 43 systems in the state of California. They compared the reported capital and O&M costs with those of 13 EPA Demonstration projects that use Adsorptive

8 Frey et al. report projected capital and O&M costs for six groundwater systems serving more than 100,000 customers. This definition of "large system" differs from that used by EPA by an order of magnitude.

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media (specifically Bayoxide E33). In addition, they compare the realized costs with EPA's affordability threshold (i.e., the total annual household water bill considered affordable) as well as the available expenditure margin for a revised MCL (i.e., the remainder of the threshold amount after subtracting off estimates of annual household water bills) reported in the economic analysis.

Although they find that the median annualized costs for California systems fall within the expected household cost for compliance with the Arsenic Rule of $0.01-$5.05/1,000 gallons (2008$), they report that 22% of the systems had annualized costs that exceeded these amounts; 19% had costs greater than EPA's expenditure margin; 15% had costs greater than EPA's affordability threshold for drinking water. However, in making these comparisons, they admit their assumption that the treatment technology in operation at each location is used to treat all water sources on the property. This assumption could result in an overestimate of costs as "not all the water for the system requires arsenic treatment." They also find that compared to California systems using similar technologies, the selected EPA demonstration sites reported lower median and maximum annualized costs. Specifically, compliance costs among systems in California employing similar technologies were $0.09/1000 gallons higher than the 13 selected EPA demonstration projects, with the demonstration projects enjoying somewhat lower labor costs but higher media replacement costs than California systems.

3.2 Data for evaluating ex post costs

We explored several source categories for ex post cost data including publicly available data on water systems and arsenic contaminant levels, EPA's office of research and development (ORD) Demonstration Projects, consultations with industry compliance experts as well as information provided by state authorities and associations in areas known to have levels of arsenic in drinking water exceeding the MCL. We discuss our findings in more detail below.

Publicly available data. A considerable amount of basic operating information (including population served, location, ownership, waters sources, contaminant concentrations, existing treatment) for public water systems is available from SDWIS and the community water system survey.[9,10] As a matter of fact, EPA used these two publicly-available databases as its primary sources of data for the

9 See http://www.epa.gov/enviro/facts/sdwis/search.html.

10 See http://water.epa.gov/infrastructure/drinkingwater/pws/cwssvr.cfm.

Safewater XL model to estimate regulatory costs for the universe of public and private water systems. However, gaps still remain in the publicly-available data that prevent the robust estimation of the realized costs of complying with the Arsenic Rule (US EPA, 2014). These gaps include mitigation strategies pursued by each system out of compliance with the new arsenic standard and the costs associated with installation and operation of these technologies (O&M costs and capital expenditures).

ORD demonstration projects. In October 2001, EPA embarked on a project to help small CWSs (<10,000 customers) research and develop cost-effective technologies to meet the new arsenic standard. As part of the Arsenic Rule Implementation Research Program, EPA's ORD conducted three rounds of full-scale, onsite demonstrations of arsenic removal technology, process modifications and engineering approaches for small systems from 2005 to 2007. In total, EPA conducted 50 arsenic removal demonstration projects in 26 states in the US. Treatment systems selected for the projects included 28 adsorptive media (AM) systems, 18 iron removal (IR) systems (including two systems using IR and iron addition (IA)) and coagulation/filtration (CF) systems (including four systems using IR pretreatment followed by AM), two ion exchange (IX) systems, and one of each of the following systems: reverse osmosis (RO), point-of-use (POU) RO, POU AM, and system/process modification.[11] Of the 50 projects, 42 were CWSs and eight were NTNCWSs.

The report "Costs of Arsenic Removal Technologies for Small Water Systems: U.S. EPA Arsenic Removal Technology Demonstration Program" (US EPA, 2011a) summarizes the cost data across all demonstration projects grouped by the type of technology. Total capital costs and O&M costs are presented for each treatment system. Capital costs are broken down by equipment, site engineering, and installation costs. Factors affecting capital costs include system flow rate, construction material, media type and quantity, pre- and/or post-treatment requirements, and level of instruments and controls required. The O&M costs for each treatment system are broken down by media replacement, chemical use, electricity and labor.

Compliance assistance engineering firms. Water systems needing to respond to the new arsenic standard may hire engineering firms to aid in designing and installing appropriate water treatment systems. As these firms would likely have detailed cost information for projects in which they were involved, we reached out to several and enlisted the assistance of two engineering firms,

11 Treatment technologies were selected from solicited proposals.

Malcolm Pirnie and Wright-Pierce.[12,13] Specifically, Malcolm Pirnie provided cost information for seventeen water systems located in California and Arizona ranging in size from 0.4 mgd (million gallons per day) to 6 mgd. The treatment technologies for these systems included three ion exchange (IO), one reverse osmosis (RO) and one point-of-use reverse osmosis (POU-RO), one activated alumina (AA), five granular ferric oxide (GFO), three granular iron media (GIM), one iron-enhanced media and one blending plan. Wright-Pierce provided cost information for two water systems which used greensand filtration as the treatment technology. The two water systems are located in Maine – one in the town of Lisbon and the other in the town of South Berwick.

Independent associations and state agencies. Four independent associations and four states (i.e., Maine, Michigan, Nevada and Washington) responded to our request for information.[14] Even though none were able to provide information on the costs of compliance strategies, they did provide interesting information about compliance strategies pursued by systems and related shortfalls. According to the associations and states, while systems did use BATs, adsorptive media was also widely used. In Maine the majority of systems (67%) employed adsorptive media while the most widely used strategy in Washington was oxidation/filtration (33%) followed by adsorptive media (25%). In Michigan sixty-three of the systems (or 54%) opted for the installation of some sort of technology with most utilizing either iron-based adsorptive media, coagulation/filtration or manganese dioxide/greensand process. Systems also used non-treatment options. In Washington non-treatment options (including abandoning a contaminated source, drilling new wells, etc.) represented another 17% of the mitigation strategies utilized with blending not far behind at 14% while 23 systems (20%) found new sources of groundwater and 9 (or 8%) connected to municipal water systems in Michigan.

Certain technologies require access to sanitary sewers to dispose of backwash water containing arsenic residuals. Even though they did not provide actual cost data, both the states and associations provided anecdotal information that disposal of this backwash water increased the costs of compliance and that EPA underestimated this cost. As in the other states, Nevada said adsorptive media figured prominently in the treatment strategies employed especially among

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12 Malcolm Pirnie provided technical support to EPA during the development of the *Technology and Cost Document* for the Arsenic Rule.

13 Internal review of this document raised concerns about the potential bias associated with capital cost estimates provided by engineering firms in that they might capture other capital improvements unrelated to arsenic mitigation.

14 For a list of associations and states who responded to our requests, please see Section 4.3.2 in US EPA, 2014.

systems without access to a sanitary sewer for disposal of backwash. Even when systems did have access to sanitary sewers, industrial pretreatment, bio-solids or NPDES concerns of the wastewater treatment facility often precluded systems from utilizing the sanitary sewers for disposal of backwash. Even though Michigan did not provide any cost data to substantiate this statement, they contend that disposal of backwash "in many cases doubled the cost amount of original arsenic removal system." According to the association of California water agencies (ACWA), more stringent requirements in California related to the management of arsenic residuals were a key driver in the selection of treatment technologies and often resulted in significantly higher compliance costs in California (ACWA, 2011).[15]

4 Ex post assessment of compliance cost

4.1 Regulated universe

All public water systems, which include publicly- and privately-owned CWS and NTNCWS, could potentially be affected by the Arsenic Rule. In addition to being classified by the number of people served by a water system (system size), public water systems are also classified by their water source: surface water vs. ground water. EPA primarily used a December 1998 "snap shot" of SDWIS to characterize the universe of water systems that could potentially be affected by the Arsenic Rule. At the time of the rulemaking, there were a total of 63,984 public/private ground water systems and 11,843 public/private surface water systems that could be potentially affected by the rule. Most of these systems were CWS – 54,352 – while the remaining 20,255 were NTNCWS. The majority (>90%) of the CWS served fewer than 10,000 people.

Recall that the Arsenic Rule was promulgated in 2001 but water systems had until 2006 to meet the new MCL. Looking at the SDWIS summary data for these years, it appears that the size of the regulated universe has decreased from the 1998 baseline. While the differences are not substantial, decreases are apparent for both CWSs and NTNCWSs. In 2001 there were a total of 53,783 CWSs and 20,095 NTNCWSs while in 2006 there were a total of 52,339 CWSs and 19,045 NTNCWSs. Most of the decreases in both years were for systems that serve 500 or

15 EPA's economic analysis of the Arsenic Rule captures only the costs of the federal regulation, not the costs of more stringent state regulations.

fewer people. The number of systems serving fewer than 500 persons has continued to decrease. The number of systems decrease another 1% from 2006 to 2008. The decline in these systems over time is most likely due to states' restructuring efforts such as having small systems connect to large, publicly-owned systems or restricting the number of new systems serving fewer than 500 from being created (US EPA, 2011b).

4.2 Baseline information

EPA relied on MCL compliance monitoring data from 25 states to develop the arsenic exposure and occurrence database (AEOD) (US EPA, 2000b). These state data were representative of almost every ground and surface water CWS in the state in addition to many NTNCWSs. The data sets also contained multiple samples from the individual systems that showed how arsenic levels varied over time or across locations within the system. From these data, EPA developed an estimate of national baseline arsenic occurrence to predict the percentage of CWSs that would have one source above the various MCLs. However, there are some limitations to using the AEOD. While most regions of the US are represented in the database, few states in the Southeast, Mid-Atlantic and New England area are included. Among the states represented, the arsenic reporting limits varied. Even though the EPA developed statistical methods to analyze values below the detection limit, the lack of consistent arsenic occurrence measurements across states is a drawback to the AEOD (Frost, Muller, Petersen, Thomson, & Tollestrup, 2003). To the best of our knowledge, EPA has not updated the AEOD since the Arsenic Rule was promulgated.

When EPA was developing the AEOD, they examined other arsenic data sources such as the National arsenic occurrence survey, the United States Geological Society ambient ground water arsenic databases, the national inorganics and radionuclides survey, and the metropolitan water district of Southern California survey, but each of the databases had limitations which prevented their use. Instead, EPA used these databases as comparison tools to check the arsenic concentrations predicted by the AEOD (US EPA, 2000b).

4.3 Methods of compliance

In the economic analysis for the Arsenic Rule, EPA presented estimates of unit costs and national system treatment costs separately for three system categories: small and large CWSs and NTNCWSs.[16] In order to obtain these estimates, EPA made assumptions about the number and types of systems that would need to treat their water; the type of treatment technology they would adopt; and the cost of installing and operating that technology. Ultimately, the actual compliance methods chosen by water systems depend not only on arsenic concentrations and the size of the system but also on location specific characteristics (e.g., iron levels in the water, pH, etc.), treatment methods already in use, and availability of alternative water sources.

At the time of the arsenic rule-making, iron-based adsorptive media was in the pilot and research phase, so it was not identified as a BAT nor was it included in EPA's compliance forecast for the cost analysis. However, the technology's effectiveness has since been demonstrated by EPA and others. As evidenced by the technologies selected for the ORD Demonstration Projects and responses from the compliance experts, states, and independent associations to our inquiries, iron-based adsorptive media has emerged as the preferred treatment technology for mitigating arsenic contamination. In particular, Malcolm Pirnie indicated that adsorption to granular iron media (GIM) has been widely used at wellheads and in POU treatment systems. They also indicated that Granular Ferric Hydroxide or variations of this media have been used frequently.

In addition to treatment technologies, Malcolm Pirnie asserted that non-treatment options such as blending with low or arsenic free water, turning off wells with elevated levels of arsenic, or selective well screening to draw water from regions of the aquifer with low arsenic levels were also used. Malcolm Pirnie provided data on one utility in Central Arizona that used a blending plan. The total treatment capital cost reported by this utility was $15,000. The states also indicated that systems used non-treatment options that included blending, finding new sources of groundwater and connecting to municipal water sources. Non-treatment options such as blending and drawing water from another area in the aquifer with low arsenic levels were also used and are not considered in the economic analysis.

Wright-Pierce indicated that they were most familiar with greensand filtration. The pilot testing for their two systems showed greensand filtration to be the best technology for removing arsenic. Wright-Pierce did indicate that innovation has occurred within greensand filtration – their two systems used Pureflow high rate media which allowed for a higher filtration rate and fewer filters.

16 The economic analysis was prepared by Abt Associates, Inc., for the Office of Water and is available here: http://water.epa.gov/lawsregs/rulesregs/sdwa/arsenic/upload/arsenicdwrea.pdf. (US EPA, 2000a).

4.4 Ex post compliance cost

For the ex post assessment, we focus on the water system information and treatment technology costs reported by the ORD Demonstration Projects. Using the ORD data, we make some general comparisons with the ex ante cost estimates. First, we consider the realized capital costs reported for each of the systems and plot these against the predicted values generated using EPA's cost curves. In so doing, we compare ex post costs for these systems with the predicted values. As we have access to cost information for all of the demonstration projects, this is an extension of the work presented in Gurian et al. (2006).

Second, using information on the design flow rate for each of the systems, we estimate a pseudo ex ante estimate using the cost curves derived by EPA for that given technology. We then compare this estimate with the realized costs reported for each system. In this way, we attempt to determine how well the cost curves performed. Because cost curves were not developed by EPA for all of the technologies represented in the data, we are limited in the comparisons we can make with this methodology.

We also present the water system information and treatment technology costs reported by the two engineering firms: Malcolm Pirnie and Wright-Pierce. However, we do not make comparisons with ex ante cost estimates since it is possible that capital and O&M costs for other activities conducted concurrently with the arsenic mitigation are intermingled. For example, construction costs provided by the engineering firms for some systems may include the costs of upgrades to increase the capacity of the system or replacement of existing equipment that are unrelated to the Arsenic Rule but are performed while the system is installing a technology to reduce arsenic. However, even with the addition of the data on these nineteen systems from Malcolm Pirnie and Wright-Pierce, our data remain too limited to draw robust conclusions on whether EPA over or under-estimated costs associated with specific technologies.

4.5 ORD demonstration projects: total reported capital and o&m costs

Adsorptive media. For the 28 water systems that selected adsorptive media (AM) technology, seven systems were NTNCWS and 21 systems were CWS (there are 28 water systems because Klamath Lake has three POU AM systems). Arsenic concentrations ranged from 12.7 to 67.2 μg/L across the sites. Arsenic removal capacity of AM is highly dependent on pH. Most AM absorb arsenic more effectively at

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a pH value of 5.5–7.5, with adsorptive capacity increasing as pH decreases. Adjusting the pH value of the water can increase the adsorptive capacity and lower the operating costs but the additional pH control equipment increases both the complexity of the system as well the capital cost of the system. Source water pH values ranged from 6.9 to 9.6 across the sites. Source waters at seventeen sites had a pH value >7.5, and seven of these 17 sites adjusted the pH value of the water. Table 1 summarizes design flow rate, average flow rate, total capital and O&M costs for the 28 water systems.

Iron removal or coagulation/filtration. Of the 50 demonstration sites, eighteen sites used iron removal (IR) or coagulation/filtration (CF) as the main treatment technology. Iron removal or oxidation filtration processes involve passing water through a greensand filter to remove iron and arsenic. Four of the eighteen systems that used IR also followed treatment with adsorptive media (AM) to remove iron and arsenic. The four systems primarily used IR as protection against fouling the AM with iron. Table 2 summarizes the location, technologies, design and average flow rate, total capital and O&M costs for the IR/CF water systems. Two of the eighteen sites were NTNCWSs. Arsenic concentrations in source waters ranged from 11.4 to 84.0 μg/L.

Other arsenic treatment technologies. Table 3 summarizes the location, technologies, flow rates, total capital and O&M costs on two systems which use ion exchange (IX), one system which used reverse osmosis (RO), and two point-of-use (POU) demonstration projects. At the Klamath Falls site, eight POU AM units were installed under a sink or inside a drinking water fountain in eight college buildings. At the Homedale site, POU RO units were installed in nine homes. Arsenic concentrations in source waters ranged from 18.2 to 57.8 μg/L. The presence of co-contaminants in source waters influenced the selection of treatment technology for the different sites.

Industry compliance engineering firms. Table 4 summarizes the location, treatment technology, design flow rate and total capital costs provided by Malcolm Pirnie. Six of the facilities used BAT options to reduce arsenic levels – three ion exchange, two reverse osmosis, and one activated alumina. Seven of the utilities used some form of an adsorption technology while one utility choose blending, a non-treatment option. Capital costs are actual costs incurred by the utilities. Although we only report either actual or median total capital costs, when available, Malcolm Pirnie did break down capital costs by treatment equipment and materials, waste disposal equipment and materials, construction, land, engineering, bench and pilot testing, permitting, and other. Malcolm Pirnie did provide O&M costs for a few facilities but because it was unavailable for most facilities, we do not report O&M costs.

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Table 1 Summary of ORD adsorptive media demonstration sites.

State	Demonstration location (Site ID)	Technology	Design flow rate (gpm)	Average flow rate (gpm)	Total capital costs ($)	Total O&M costs ($/kgal)
ME	Wales (WA)	Iron modified media (alumina based)	14	10.4	$16,475	$22.88 $10.44 $5.52#
NH	Bow (BW)	Iron modified media (silica based)	40	41	$166,050	$5.11
NH	Goffstown (GF)	Granular ferric oxide	10	13	$34,201	$2.34
NH	Rollinsford (RF)	Granular ferric oxide	120	82	$131,692	$3.59*
VT	Dummerston (DM)	Iron modified media (alumina based)	22	6.1	$14,000	$10.86
CT	Woodstock (WS)	Titanium oxide media	20	16.4	$51,895	No estimate**
CT	Pomfret (PF)	Iron modified media (resin based)	15	9.6	$17,255	$7.67
MD	Stevensville (SV)	Granular ferric oxide	300	207	$211,000	$0.61
OH	Buckeye Lake (BL)	Granular ferric oxide	10	On demand	$27,255	No estimate**
MI	Brown City (BC)	Granular ferric oxide	640	564	$305,000	No estimate**
IL	Geneseo Hills (GE)	Granular ferric oxide	200	32	$139,149	No estimate**
SD	Lead (LD)	Iron modified media (resin based)	75	71.5	$87,892	$0.98
TX	Alvin (AL)	Granular ferric oxide	150	129	$179,750	$0.61
TX	Bruni (BR)	Granular ferric oxide	40	40	$138,642	No estimate**
TX	Wellman (WM)	Granular ferric oxide	100	91	$149,221	No estimate**
NM	Anthony (AN)	Granular ferric oxide	320	260	$153,000	$0.75
NM	Nambe Pueblo (NP)	Granular ferric oxide	160	114	$143,113	No estimate**
NM	Taos (TA)	Granular ferric oxide	450	503	$296,644	No estimate**
AZ	Rimrock (RR)	Granular ferric oxide	45	31	$88,307	$0.86
AZ	Tohono O'odham Nation (TN)	Granular ferric oxide	63	60.1	$115,306	No estimate**

(**Table 1** Continued)

State	Demonstration location (Site ID)	Technology	Design flow rate (gpm)	Average flow rate (gpm)	Total capital costs ($)	Total O&M costs ($/kgal)
AZ	Valley Vista (VV)	Iron modified media (alumina based)	37	36	$228,309	$2.47
OR	Klamath Falls (KF)[a]					
	(a)	Iron modified media (resin based)	30	On demand	$55,847	No estimate**
	(b)	Granular ferric oxide	60	On demand	$59,516	$5.37
	(c)	Titanium oxide media	60	On demand	$73,258	No estimate**
NV	Reno (RN)	Granular ferric hydroxide	350	275	$232,147	$5.69
CA	Susanville (SU)[a]	Iron modified media (alumina based)	12	9.3	$16,930	$12.06
CA	Lake Isabella (LI)	Iron modified media (resin based)	50	23	$114,070	No estimate**
CA	Tehachapi (TE)	Zirconium oxide media	150	79.3	$76,840	$1.16

[a]Non-transient non-community water systems.
#Associated with three replacement media types: A/I Complex, GFH, and CFH.
*Estimated Cost– did not replace media.
**No estimate of total O&M but estimates of media replacement costs, electricity, chemicals and labor costs are provided.

In addition, Wright-Pierce provided cost information for two water systems in Maine, both of which used greensand filtration as the treatment technology. The Willow Drive Pump station in the South Berwick water district serves a population of 3280 and has a design flow rate of 0.792 mgd. Capital costs associated with this project were reported as $1,329,798 in 2003 and O&M costs of $52,906 per year. The Moody River Road Filter plant serves a population of 6250 with a design flow rate of 1 mgd. Capital costs associated with this project were reported as $2,582,326 in 2005 and O&M costs of $69,609 per year.

5 Ex ante and ex post cost comparisons

Our only source of pre-regulatory cost information is the cost curves developed by EPA. At this time we use only one source of post-regulatory costs: ORD

Table 2 Iron removal (IR) and coagulation/filtration (CF) systems.

State	Demonstration location (Site ID)	Technology	Design flow rate (gpm)	Average flow rate (gpm)	Total capital costs ($)	Total O&M costs ($/kgal)
IN	Goshen (GS)[a]	IR + AM	25	15.2	$55,423	$2.90
IN	Fountain City (FC)[a]	IR	60	47	$128,118	$2.26
MN	Sauk Centre (SC)	IR	20	4	$63,547	$0.36
UT	Willard (WL)	IR + AM	30	9.3	$66,362	$1.93
WI	Delavan (DV)	IR	45	20 (max)	$60,500	$0.26
IL	Waynesville (WV)	IR	96	84	$161,560	$0.65
MN	Climax (CM)	IR/IA	140	132	$270,530	$0.29
PA	Conneaut Lake (CL)	CF	250	153	$216,876	$0.46
MT	Three Forks (TF)	CF	250	206	$305,447	$0.18
MN	Sabin (SA)	IR	250	231	$287,159	$0.43
OH	Springfield (SF)	IR + AM	250	89	$292,252	$0.33
MN	Stewart (ST)	IR + AM	250	190	$367,838	$0.16
MI	Sandusky (SD)	IR	340	163	$364,916	$0.27
WI	Greenville (GV)	IR	375	285	$332,584	$0.55
DE	Felton (FE)	CF	375	263	$334,297	$0.31
MI	Pentwater (PW)	IR/IA	400	350	$334,573	$0.17
WA	Okanogan (OK)	CF	550	538	$424,817	$0.18
LA	Arnaudville (AR)	IR	770	335	$427,407	$0.07

[a]Non-transient non-community water systems.
IA, supplemental iron addition; AM, adsorptive media.

Demonstration Projects, of which a significant share is based on iron-based adsorptive media. To compare ex ante costs with our limited ex post cost data, we plot our ex post cost data against the capital cost curves used by EPA for treatment technologies recommended for smaller systems – activated alumina, ion exchange and greensand filtration. The capital costs from the ORD Projects are plotted in Figures 1 and 2.[17] To keep the figures visually simple, Figure 1 plots the capital cost data for the demonstration projects that had a design flow rate between 0.01 mgd and 0.5 mgd while Figure 2 plots the data for projects with a design flow rate >0.5 mgd. The results are mixed. In 42 out of 49 demonstration projects, realized capital costs are below the 2006 cost curve estimates for at least one of the three technologies.[18]

17 Total capital costs for the ORD demonstration projects were converted to 2006 dollars from the year of construction using the Engineering News Record Construction Cost Index. See Appendix 4.2 in US EPA, 2014 for cost curve equations in 2006$.

18 Two POU ORD projects did not provide design flow rate so they are not included on the figures.

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Table 3 Other arsenic treatment technologies: ion exchange (IX), Reverse osmosis (RO), and Point-of-Use (POU).

State	Demonstration location (Site ID)	Technology	Design flow rate (gpm)	Average flow rate (gpm)	Total capital costs ($)	Total O&M costs ($/kgal)
ME	Carmel (CE)[a]	RO	1200 gpd	0.8 (permeate); 1.2 (reject)	$20,542	$12.89
OR	Klamath Falls (KF- POU)[a]	POU AM	NA	NA	$1216	
ID	Homedale (HD)	POU RO	NA	NA	$31,877.50	$201.50/yr (total)
ID	Fruitland (FL)	IX	250	157	$286,388	$0.62
OR	Vale (VA)	IX	540	534	$395,434	$0.35

[a]Non-transient, non-community water system.
AM, Adsorptive media; NA, not applicable.

5.1 Comparison of technology costs

This section presents the actual capital costs and O&M costs compared to predicted costs obtained using EPA cost curves for two BAT compliance options: Ion Exchange and Greensand Filtration.[19] Before presenting these comparisons, there are a few points to note. First, there is more uncertainty surrounding operating cost estimates than capital cost estimates because of the difficulties in separating incremental activities related to rule compliance from general operating activities. Second, and most importantly, we do not have enough cost data to draw robust conclusions about whether EPA over or under-estimated technology costs. We present the cost comparisons for these technologies here to simply illustrate the evaluation we could make if we had more data on ex post technology costs.

Ion exchange. Table 5 presents total capital costs (CapEx) and total O&M costs (OpEx) for the two ORD demonstration projects that used ion exchange (IX). Using the design flow rate and average flow rate of the systems, we use EPA's cost equations for IX to predict the capital and O&M costs for this technology (EPA estimate). Column 5 represents the percentage error between these EPA estimates

19 We only compare the ORD projects that used a BAT. We do not compare the projects that used a combination BAT and non-BAT (e.g., iron removal (IR) and AM) or a technology that was in the same class but a variation of a BAT. For example, we do not compare ORD projects that used coagulation filtration (CF) to EPA's BAT because EPA assumed modified coagulation/filtration and not new installation of the technology. Also Greensand filtration is the only form of IR or CF that was a BAT. Although similar, other IR technology used by the demonstration projects was not a BAT.

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Table 4 Median and reported values of design flow rate and total capital costs by treatment technology for select systems in California and Arizona (Malcolm Pirnie).

Type of value	Treatment technology	Design flow rate (mgd)	Total capital costs ($)
Median	Adsorption (10)	3.6	$1,423,440
	Ion exchange (3)	5.76	ANR
Reported	Reverse osmosis (1)	1.44	<$240,000
	Reverse osmosis (1)	POU	$400
	Activated Alumina (1)	0.86	<$1,575,000
	Blending plan (1)	4.18	$15,000

ANR, Available but not reported because we cannot verify that the reported costs are specific to arsenic mitigation.
(#) Either number of facilities used in the median calculation or the number using a treatment technology.

and the realized costs reported by ORD demonstration project sites. A positive (negative) percentage error means that EPA estimate was higher (lower) than actual costs incurred by the individual system.

EPA's estimates of capital costs were mixed. For the smaller system, as measured by design flow, EPA estimate was lower than the actual cost of the project

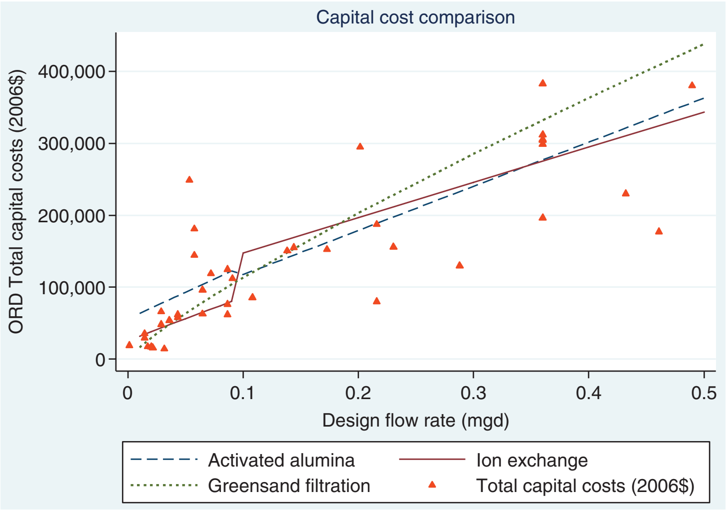

Figure 1 Capital cost comparison by design flow rate (0.01–0.5 mgd) – EPA cost curves vs. ORD demonstration projects[a].
[a]The kinks in the cost curves for activated alumina and ion exchange are the result of different cost curves being used for design flow rate (mgd) > and <0.1 mgd. See Appendix 4.2 in US EPA, 2014 for a description of the cost curves.

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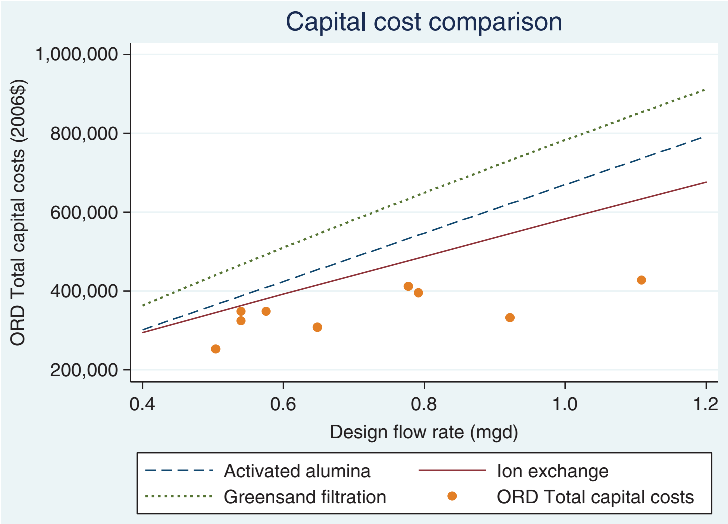

Figure 2 Capital cost comparison by design flow rate (0.5–1.2 mgd) – EPA cost curves vs. ORD demonstration projects.

and higher than the actual cost of the project for the larger system. For both projects, EPA's cost curves predicted lower O&M costs than the actual project costs.

Greensand filtration. Two community water system ORD Demonstration Projects used Greensand filtration (GF) as a treatment technology. Table 6 presents total capital costs (CapEx) and total O&M costs (OpEx) for these two systems. Using the design flow rate and the average flow rate of the systems, we use EPA's cost equations employed in the economic analysis for GF to estimate the capital and O&M costs for this technology (EPA Estimate). Column 5 represents the percentage error between EPA estimate and the costs reported by ORD Demonstration Project sites. A positive (negative) percentage error means that EPA estimate was higher (lower) than the actual project costs for those systems. In the case of the GF technology, one ORD Demonstration Project had capital costs that were slightly higher than EPA estimate (–1%) while the other had capital costs that

Table 5 Cost comparisons – ion exchange (2006$).

	Design flow/average flow (mgd)	ORD project costs	EPA estimate	% Error
CapEx	0.36	$311,988	$275,245	−12%
	0.78	$411,632	$477,021	16%
OpEx	0.23	$55,735	$34,180	−39%
	0.77	$102,258	$43,180	−58%

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Table 6 Cost comparisons – greensand filtration (2006$).

	Design flow/average flow (mgd)	ORD project costs	EPA estimate	% Error
CapEx	0.14	$150,692	$149,082	−1%
	0.36	$196,150	$332,473	69%
OpEx	0.12	$26,767	$19,341	−28%
	0.22	$33,457	$27,139	−19%

were significantly lower than projected (69%). For both projects, predicted O&M cost were slightly lower than the realized cost.

6 Overall implications and study limitations

As the introduction and the literature survey make clear, even the most credible analysis of compliance costs (done before implementation) will vary from actual costs for a large number of reasons. For example, the number of water systems exceeding the standard could be larger or smaller than predicted before the rule. Or, as in the case of arsenic, innovation, impossible to forecast, may have reduced the costs. As indicated by the states and associations who provided information, adsorptive media, which was still in the experimental stage when the rule was developed, proved to be effective at reducing arsenic levels and was widely adopted as a treatment option.

This case study was particularly challenging in that the systems affected by the new arsenic standard are heterogeneous. This fact is made apparent in the limited information we gathered from states and associations. The differences among water systems across the county necessitated that a variety of treatment technologies, even some non-treatment options, be used to reduce arsenic levels. In addition to the heterogeneity of sites, it is also challenging to distinguish costs attributable to compliance with the Arsenic Rule from costs incurred by systems as a result of complying with other regulations or to meet other needs of the system. For example, some treatment technologies, such as ion exchange, are capable of removing other contaminants (e.g., uranium) in addition to arsenic. The portion of the treatment cost attributable to arsenic compliance can be difficult to distinguish from the cost of contaminants being removed for other regulations. Additionally capital costs may also include costs associated with other projects unrelated to arsenic treatment, including upgrades that increase the overall capacity of the system or replace existing equipment at the treatment plant. Because systems may perform other types of maintenance projects concurrent with their response to the Arsenic Rule, it can be difficult to isolate the costs attributable to the rule. These factors all add to the analytic challenge of how to evaluate the costs faced by systems affected by the Arsenic Rule.

With no comprehensive or even representative data on costs or mitigation strategy selected, our options were limited. Short of conducting a survey of community water systems to gather information on treatment methods used and the costs associated with those methods, we found no other means of collecting the necessary data. Instead, we relied on limited information collected from compliance engineering firms and EPA demonstration projects which have their own potential biases. For example, the ORD projects rely on emerging technologies that were not entirely understood by the vendors. In addition, the price for adsorptive media was not well-established and, because of the speed at which EPA needed to implement the demonstration program, there may not have been sufficient time to negotiate the most competitive media prices.

Generally, little to no pilot testing was conducted at demonstration sites to optimize the design and installation of the technologies at a given facility prior to the selection of a technology and its implementation. On the other hand, vendors wishing to establish their technologies as cost-effective alternatives may have offered EPA more appealing prices. Again, because the goal of the program was to demonstrate the effectiveness of various alternative treatment technologies, non-treatment alternatives were not considered and are therefore not represented in the data. However, because of the detailed nature of the data, they nevertheless provided useful information.

While we do make comparisons of EPA predicted costs and realized costs from the ORD Demonstration Projects, these comparisons are for illustrative purposes only. We plot all of the capital cost data from the ORD Demonstration Projects against the cost curves for the compliance technologies recommended for smaller systems and find that EPA methodology overestimates capital costs in most cases, especially as the size of the system increases (as measured by the design flow rate). We also compare EPA predicted costs and realized costs from the four ORD Demonstration Projects for two specific BATs (ion exchange and greensand filtration) but make no judgments. Because the number of observations in our data set is very small compared to the number and heterogeneity of the systems affected by the Arsenic Rule, we cannot draw any conclusions regarding EPA's technology cost estimates. Our data capture the costs of treatment technologies for a very small percentage of systems affected by the arsenic standard and as such, our results are not generalizable across affected systems. Instead, our illustrative comparisons offer insights into how we might proceed if better and more comprehensive data were available.

We find that this effort illustrates the characteristics of an environmental control problem that make case study analysis extremely difficult and expensive. Despite our best efforts, our data do not provide enough coverage of CWSs to make any assessment of how ex post costs deviate from EPA's ex ante estimates. As discussed below, the heterogeneity of the affected water systems presents major obstacles to comparing ex post and ex ante costs. These factors and our lessons learned from doing this case study should be considered when designing future case studies assessing ex ante and ex post costs. We do offer limited comparisons of predicted cost estimates obtained using methodologies employed by EPA in the economic analysis with the data we collected on realized compliance costs for the 50 systems.

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References

Association of California Water Agencies (ACWA). (2011). Correspondence with Abby Schneider.

Bitner, K., Thomson, B., & Chwirka, J. (2001). The cost of compliance with a new drinking water standard for arsenic in New Mexico. *New Mexico Geology, 23*, 10–12.

Chen, A. S. C., Wang, L., Oxenham, J. L., & Condit, W. E. (2004). "Capital Costs of Arsenic Removal Technologies, U.S. EPA Arsenic Removal Technology Demonstration Program Round 1." EPA/600/R-04/201.

Frey, M. M., Chwirka, J., Narasimhan, R., Kommineni, S., & Chowdhury, Z. (2000). "Cost Implications of a Lower Arsenic MCL." AWWA Research Foundation and American Water Works Association, Denver, CO.

Frost, F. J., Muller, T., Petersen, H. V., Thomson, B., & Tollestrup, K. (2003). Identifying US populations for the study of health effects related to drinking water arsenic. *Journal of Exposure Analysis and Environmental Epidemiology, 13,* 231–239.

Gurian, P. L., Bucciarelli-Tieger, R., Chew, M., Martinez, A., & Woocay, A. (2006). "Validating pre-regulatory cost estimates for the revised arsenic MCL." Proceedings of the AWWA Annual Conference and Exposition in San Antonio, TX.

Hilkert Colby, E. J., Young, T. M., Green, P. G., & Darby, J. L. (2010). Costs of arsenic treatment for potable water in California and comparison to U.S. Environmental Protection Agency affordability metrics. *Journal of the American Water Resources Association*, *46*(6), 1238–1254.

Kopits, Elizabeth, McGartland, Al, Morgan, Cynthia, Pasurka, Carl, Shadbegian, Ron, Simon, Nathalie, Simpson, David, & Wolverton, Ann. (2014). Retrospective cost analyses of EPA regulations: a case study approach. *Journal of Benefit Cost Analysis*, *5*(2), 173–193.

National Drinking Water Advisory Council (NDWAC). (2001). "Report of the Arsenic Cost Working Group to the National Drinking Water Advisory Council." Available at: http://water.epa.gov/drink/info/arsenic/upload/2005_11_10_arsenic_ndwac-arsenic-report.pdf.

US Environmental Protection Agency (US EPA). (2000a). "Arsenic in Drinking Water Rule Economic Analysis." EPA 815-R-00-026. Prepared by Abt Associates, Inc. for EPA OGWDW, December.
US Environmental Protection Agency (US EPA). (2000b). "Arsenic Occurrence in Public Drinking Water Supplies." EPA 815R00023. Prepared by ISSI Consulting Group under contract 68C70005, The Cadmus Group under contract 68C99206 and ICF Consulting for EPA OGWDW.
US Environmental Protection Agency (US EPA). (2000c). "Technologies and Costs for Removal of Arsenic from Drinking Water." EPA 815R00028. Prepared by Malcolm Pirnie, Inc. under contract 68C60039 for EPA ORD.
US Environmental Protection Agency (US EPA). (2005). "Treatment Technologies for Arsenic Removal." EPA 600/S-05/006. EPA's National Risk Management Research Laboratory, November.
US Environmental Protection Agency (US EPA). (2011a). "Costs of Arsenic Removal Technologies for Small Water Systems: US EPA Arsenic Removal Technology Demonstration Program." EPA 600R11090. Prepared by Lili Wang and A.S.C. Chen, under contract EPC05057 for EPA ORD.
US Environmental Protection Agency (US EPA). (2011b). "National Characteristics of Drinking Water Systems Serving 10,000 or Fewer People." EPA 816R10022. EPA's Office of Water, July.
US Environmental Protection Agency (US EPA). (2014). "Retrospective Study of the Costs of EPA Regulations: A Report of Four Case Studies." Available at: http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0575.pdf/$file/EE-0575.pdf.

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