The costs of small drinking water systems removing arsenic from groundwater

Thomas J. Sorg, Lili Wang and Abraham S. C. Chen

ABSTRACT

The US Environmental Protection Agency (EPA) conducted an Arsenic Demonstration Program whereby the Agency purchased, installed, and evaluated the performance and cost of 50 small water arsenic removal treatment systems in the USA. A major goal of the program was to collect high-quality cost data (capital and operational and maintenance (O&M)) from the long-term operation (1–4 years) of these systems. The technologies consisted of adsorptive media (AM), iron removal (IR), coagulation/filtration (C/F), ion exchange (IX), reverse osmosis, and point-of-use devices, which reduced the arsenic to less than the EPA maximum contaminant level of 10 μg/L. This paper presents the capital and O&M cost of 48 treatment systems ranging in size from 10 to 770 gal/min (gpm) (38–2,915 L/min). The capital cost of the systems ranged from $477 to $6,171 per gpm ($126–$1,632 per L/min) of design flow and the O&M cost from $0.07 to $22.88 per 1,000 gal ($0.02–$6.05 per 1,000 L) of treated water. AM had a lower capital, but a higher O&M cost than IR, C/F, and IX. The media replacement cost for the AM systems averaged 80% of the O&M cost and was the main cause of the higher O&M cost of the AM systems.

Key words | arsenic, drinking water, technology demonstration, treatment cost

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INTRODUCTION

In 2001, the US Environmental Protection Agency (EPA) revised the arsenic maximum contaminant level (MCL) in drinking water from 0.050 mg/L (50 μg/L) to 0.010 mg/L (10 μg/L) and required public water systems to comply with the new standard by 23 January 2006 (EPA 2001, 2003a). This change in the MCL was estimated to impact approximately 5,000 small, public water systems serving populations of ≤3,300.

Although many small systems have installed treatment systems to achieve compliance with the revised arsenic standard, a significant number still face the challenge of installing a water treatment system to achieve arsenic compliance. Most of the existing, non-compliant small water systems have very limited resources and, therefore, finding a low cost, affordable technology (capital and operation and maintenance (O&M)) is of major interest to them. Although many small arsenic treatment systems have been operating for the past 6–8 years, very few data on the capital and operating costs of these systems have been collected and reported in the literature (Mohan & Pittman 2007; Hilkert *et al.* 2010). Treatment capital and O&M cost data from operated systems can be extremely useful to non-compliant, small water systems in selecting an affordable arsenic removal technology.

In 2002, the EPA initiated an Arsenic Treatment Technology Demonstration Program (ADP) with the major objective of providing information on cost-effective, small system treatment technologies. The program was funded by the EPA to reduce the financial risk of the small systems with their limited resources having to select and purchase a new, unproven technology with little or no performance or cost information available to them. A key goal of the program was to collect high-quality performance and cost data from the long-term operation (1–4 years) of full-scale systems under the real world operating conditions. To achieve this goal, the EPA purchased, installed, and

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evaluated the performance and cost of the treatment systems that were selected through a cooperative decision process involving the water systems, the state drinking water agencies, and the EPA (Wang *et al.* 2005).

Between 2003 and 2011, the EPA initially partnered with 50 small water systems in 27 different states to conduct performance evaluation studies on over 15 different, commercially available, full-scale treatment technologies operating under a variety of conditions. One utility withdrew from the program and was replaced by a single residential home, point-of-entry (POE) treatment study which reduced state participation to 26. The source waters were all ground water and the arsenic concentration in the source water ranged from 13 to 150 μg/L.

Five basic technologies were selected for study and all were fundamentally proven technologies (Chen *et al.* 1999; EPA 2003b; Amy *et al.* 2005; Mohan & Pittman 2007; Giles *et al.* 2011) for small systems. The treatment systems include: adsorptive media (AM), iron removal (IR), coagulation/filtration (C/F), ion exchange (IX), and reverse osmosis (RO). At four sites, a combination of two technologies, iron removal followed by adsorptive media (IR/AM), was installed. All of the treatment systems reduced and maintained the arsenic concentration in the treated water to below the EPA MCL of 10 μg/L.

A single or combination treatment approach was selected for demonstration at each site except for two. System modification was evaluated at a North Dakota site where an existing IR system was reducing the arsenic from around 130 to 30 μg/L (Condit *et al.* 2006). At an Oregon site (Oregon Institute of Technology), three AM systems were installed; one at the entry point (POE) of three different campus buildings as an alternative to central wellhead treatment (Chen *et al.* 2011). A map of the locations of the 50 demonstration sites is shown in Figure 1. The ADP ended on 30 October 2011 and the results from each demonstration project are documented in individual performance evaluation reports available online at www.epa.gov/nrmrl/wswrd/dw/arsenic/. A detailed report of all the cost data (capital and O&M) from these individual project reports is also available at the same website (Wang & Chen 2011).

This paper summarizes the capital and O&M costs of arsenic removal treatment systems of the ADP treating flows of 10–770 gpm (all gpm units can be converted to L/min by using a multiplier of 3.78). The capital and O&M information presented are the actual cost data obtained during the ADP performance evaluation studies. The treatment systems were purchased between 2003 and 2008 and the O&M cost data were collected during a

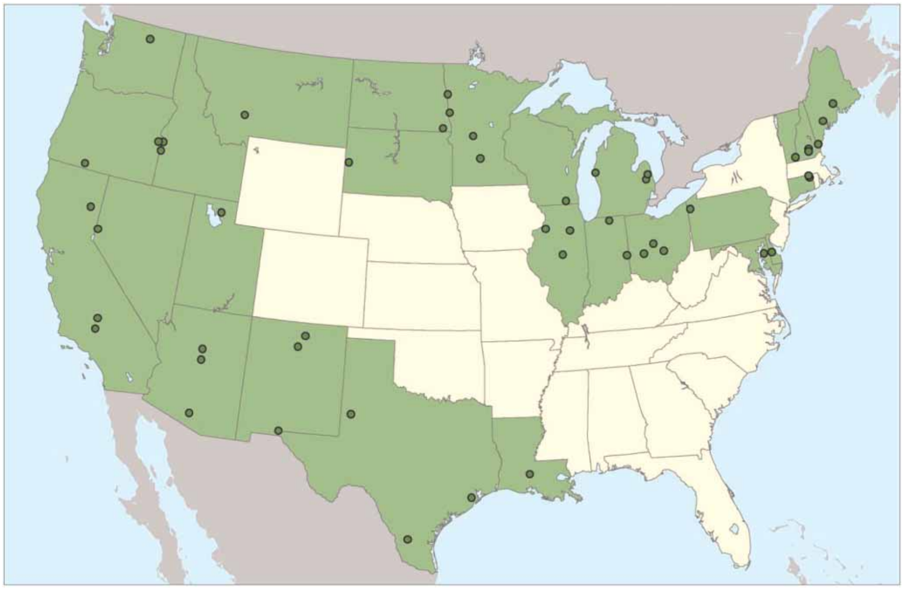

Figure 1 | Location of the 50 arsenic treatment technology demonstration program sites (states (shaded green/gray) with arsenic demonstration program site(s); o = site location). The full color version of this figure is available online at http://www.iwaponline.com/jws/toc.htm.

7 year period from 2004 through 2010. Normalizing all of the capital and O&M cost data collected during the 7 year period to 1 year would be a difficult task because of varying operational periods and the variation in designs of the individual treatment systems. Thus, the data presented are not intended to be used for precise estimates of current day or future costs of similar arsenic removal systems. The operating and capital costs presented are likely lower than current day costs due to inflation, with the current consumer price index at approximately 15% higher than the average index of the 2004–2008 year period. The cost data do, however, provide rough cost estimates and are useful for comparing the costs (capital and operating) of the different technologies and designs.

TREATMENT TECHNOLOGIES

The most frequently selected technology was the AM process that consisted of 28 systems at 26 sites in 15 different states. The 28 systems included nine different AM products with E33 (iron based media) being the most frequently used media (13 systems).

The second most frequently selected technology was IR (10 systems). Within a short operational time period, two of these systems required additional iron (i.e. ferric chloride) in order to reduce the arsenic to below 10 μg/L. Four different filtration media products were used with Macrolite® being the most commonly used media (seven systems).

Three of the four sites that installed an IR/AM combination system selected it because of the potential of iron fouling of the AM. The IR process not only helps protect the AM system from iron fouling but also removes some arsenic, thereby extending the life of the AM. The fourth dual system was selected for its capability to reduce the arsenic to very low levels. At this site, the IR system lowered the source water arsenic from 23 μg/L to slightly below 10 μg/L and the AM system further reduced the arsenic to around 1–2 μg/L at start-up.

The remaining technologies consisted of C/F (4), IX (2), and RO (1). The C/F and IR processes are very similar with both technologies using iron to remove arsenic. C/F requires the addition of an iron coagulant while IR takes advantage of natural iron in source water. Some, but not all, of the C/F and IR systems included very simple contact tanks (no flocculation). IX was selected by two water systems because their source waters contained a co-contaminant, nitrate. IX is effective in removing both arsenic (arsenate) and nitrate. The central RO system was also selected because of a co-contaminant, antimony.

Excluding RO technology, the other five technologies all use metal/fiberglass tanks to house an adsorptive media, a filtration media or an IX resin depending on the technology (Figure 2). This common design feature is a major cost component of each treatment system. The number, size, and layout of these tanks are a function of the design flow, water quality, and the arsenic removal mechanism. Ancillary equipment, such as pH adjustment, chemical feed (ferric chloride and liquid chlorine) systems, chemical contact tanks, and backwash holding tanks are additional cost items that vary with the technology and the need for additional treatment.

Table 1 provides source water quality parameters (As, Fe, and pH) and system design flows for the six treatment technology categories for the 49 systems in the study. All three water quality parameters had some impact on the selection and design of the treatment system for each site. Iron was particularly significant because of its affinity for arsenic and its potential for media fouling. When the iron concentration of the source water was above the iron secondary maximum contaminant level of 0.3 mg/L, an IR or IR/AM system was selected except for one system (AM only) (Figure 3). AM system was selected for source water with 2.3 mg/L of iron because the site had an existing water softener that reduced the iron to below 0.3 mg/L. When the iron concentration of the source water was below 0.3 mg/L, other factors came into play in the technology selection process which led the decision to select AM, C/F, IX, or RO.

COST DATA METHODOLOGY

Capital costs

A request for proposal (RFP) was solicited for each demonstration project that required the proposer to describe the treatment system and provide an estimate of capital

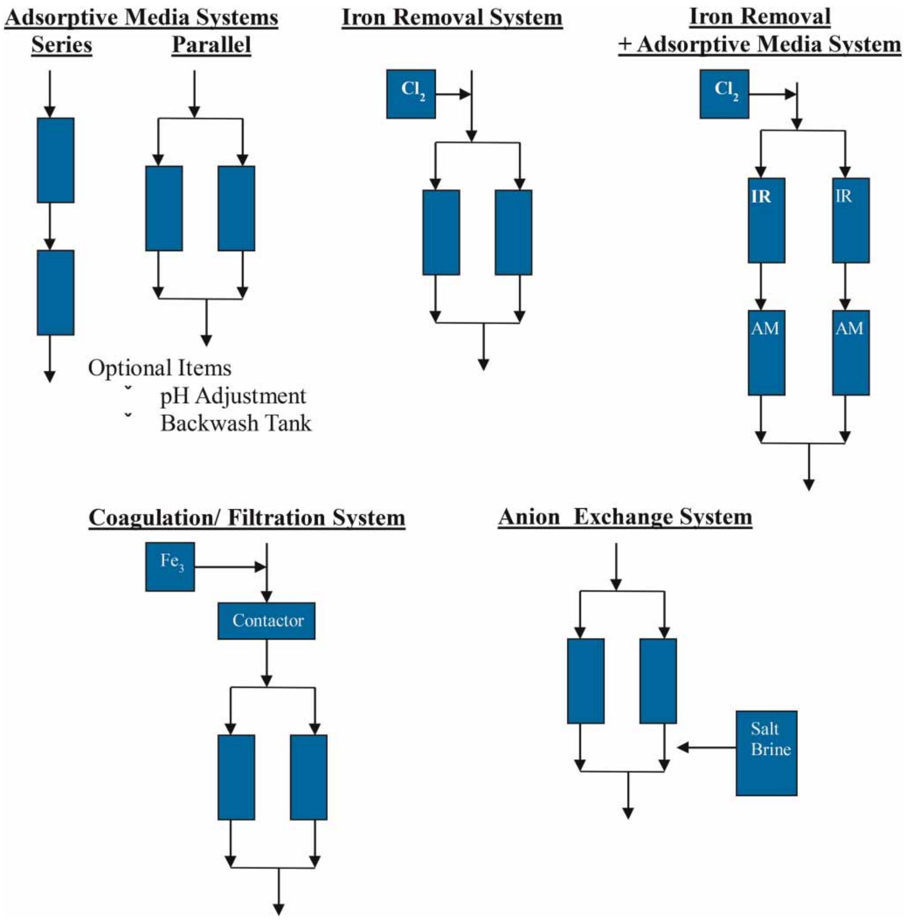

Figure 2 | Basic design of five arsenic removal treatment systems.

Table 1 | Summary of treatment system information and source water quality

Treatment systems	AM	IR	IR + AM	C/F	IX	RO
Number of systems	28	10	4	4	2	1
Design flow rate, L/m	38–2,423	76–2,915	95–946	946–2,083	946–2,040	[a]
Arsenic, μg/L	13–88	14–39	15–42	18–56	17–44	18
Iron, mg/L	<0.025–2.3	2.5–0.43	0.33–1.6	<0.025–0.16	<0.025	0.025
pH, units	6.9–9.6	6.8–7.9	7.2–7.9	7.5–8.3	7.4–8.0	7.9

[a] RO feed flow rate of 3,000 gpd (11,356 L/d) with permeate production rate of 1,500 gpd (5,678 L/d)).

cost and operating cost of the system. The number of proposals received for each project ranged from one to eight. It was not uncommon for the highest capital cost estimate to be as much as 400% more than the lowest cost estimate. Although the estimated cost was a significant factor considered in the proposal selection process, it was not the only factor. Other factors considered were the estimated performance, residuals, ease and simplicity of operation, footprint, pre- and post-treatment requirements, and adaptability to site conditions. Because the ADP was limited to small system participation, the majority of the technical proposals were received from

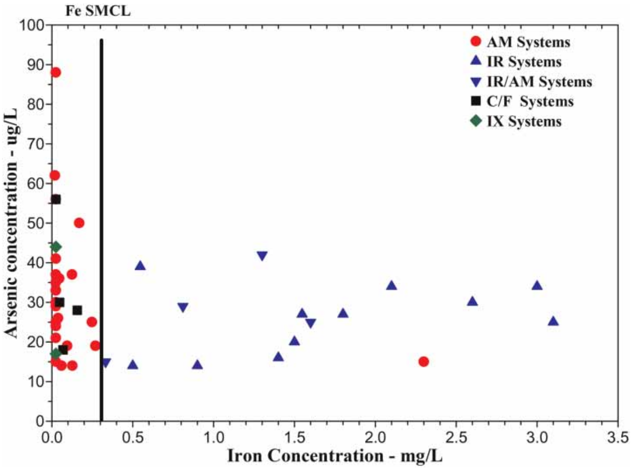

Figure 3 | Relationship of treatment system type to iron concentration of source water.

equipment vendors proposing pre-built, skid-mounted systems.

After a project proposal was selected, the equipment vendor was required to submit a more detailed cost proposal using an ADP template. This template required a breakdown of the total cost into three major categories: equipment, engineering, and installation. These three categories are the costs that make up the capital cost estimates used for comparison. In most cases, the vendors provided even greater breakdowns of the three categories. Included under the equipment cost category were items such as the skid-mounted system (tanks, piping, valves, etc.), adsorptive/filtration/resin media, miscellaneous materials and supplies and freight, user's manual, and vendor's labor. Also included were costs for chemical feed systems, such as pH control, pre-chlorination, and/or iron addition. The cost of backwash recycle equipment was provided when backwash recycle was included in system design.

The engineering category included the cost for the design, layout and footprint of the system within the building, design of the piping connections up to the distribution tie-in points in the building, and the design of the electrical connection and conduit plan. The engineering cost also included the cost for the submission of the engineering plans to the state regulators for permit review and approval. In most cases, the vendors contacted and hired (subcontractor) a local engineering firm recommended by the water system who had experience with the state permit process. The installation cost included the costs for the equipment and labor to unload and install the system, the piping tie-ins and electrical work, the loading and backwashing of the media, system shakedown and start-up, and operator's training.

The cost of any land acquisition, building construction, site preparation, storage facilities, and residual handling (if required) was outside of the scope of this program and funded separately by the host sites; thus, these items are not included in capital cost.

O&M cost

O&M costs were categorized into media replacement (AM systems only), chemicals, electricity, and labor. These data were collected by the operator using standardized data collection forms designed for the ADP. The cost data were collected primarily from the first year of system operation except for the media replacement costs, most of which were not incurred until 14–45 months into operation (depending on the media life).

Of the 28 AM systems, only 15 had to replace their exhausted media during the study period (paid for by the ADP); thus, complete O&M cost was obtainable for only these 15 systems. Two of the systems experienced multiple media change out with different types of media. For AM systems, the media replacement cost was broken down into media, labor, and other related costs, such as media analysis (toxicity characteristic leaching procedure), media disposal, and freight. The labor cost for AM replacement was the cost incurred by a contractor who provided the media replacement services.

The cost of all chemicals associated with the new treatment system, such as pH adjustment and pre-oxidation chemicals, ferric chloride, and IX brine, was paid for by the EPA under the ADP agreement with the water system. Any chemicals associated with any pre-existing system operation, such as chlorination/disinfection, softeners, fluoridation, residual treatment, etc., were paid by the host sites and not included in the O&M cost data.

The electricity cost was tracked by comparing monthly electrical bills (paid by the host sites) before and after installation of the arsenic treatment system. If the site did not have a separate meter for the arsenic treatment system, then the cost was estimated based on the power requirements of the major equipment (such as compressor, pump, etc.), the average operational hours, and the local electricity unit price. The local electricity unit price ranged from \$0.08 to \$0.14 per kWh.

Each demonstration site was provided with an Operator Labor Log Sheet to track labor hours used for routine O&M, EPA demonstration study-related activities, repairs, and miscellaneous activities. The routine O&M includes activities such as filling field logs, performing system inspection, ordering inventory, and others as recommended by the vendors. EPA study-related activities such as performing field measurements, collecting and shipping samples, and communicating with the ADP Project Study Lead, were not used in the cost analysis. The labor rate was provided by the operators.

RESULTS AND DISCUSSION

Capital cost

Total capital cost

The total capital cost and some design information of 48 treatment systems of the ADP are provided in Table 2 (AM systems) and Table 3 (all other systems except for RO). The RO system (school) information is excluded because of the unique nature of this project whereby a separate water distribution line was installed in the school to provide RO treated water to only the drinking water outlets and kitchen. The total capital cost of the systems ranged from \$14,000 for a small 22 gpm AM system to \$427,407 for a 770 gpm IR system. The total capital cost of each system plotted as a function of its design flow rate is shown in Figure 4. The linear regression of the data set yielded an R^2 value of 0.74. A visual observation of these data indicates significantly more scatter of the total costs of the systems treating flows of $\leq$100 gpm than those treating $\geq$100 gpm, particularly with the AM systems. The difference can be more clearly seen when the data are divided into two design flow categories: $\leq$100 and $\geq$100 gpm (Figure 5(a) and 5(b)).

The wide variation of the total capital costs for the systems treating $\leq$100 gpm (Figure 5(b)) can be attributed to the extensive variations of the design features of these very small systems, particularly for the AM systems. The major AM design features that impact capital cost include the empty bed contact time (EBCT), tank configuration (series vs. parallel), tank material, and the amount of instrumentation and controls. For these small AM systems, the cost of media becomes a major component of the total cost and in the ADP nine different media products were used that had costs ranging from \$40 to over \$500 per cubic foot. The EBCT, which determines the tank(s) size, varied from 1.5 to 16 min (all \$/cu ft units can be converted to \$/L by using a multiplier of 0.035). Another factor impacting the tank(s) cost is the material: carbon steel, stainless steel (SS), FRP, and polyglass. SS tanks cost more than the carbon steel tanks which cost more than FRP and polyglass tanks. Five AM systems had equipment for pH adjustment and four had backwash storage/recycle tanks, all of which increase the total capital cost. Although some water quality parameters, such as the arsenic concentration of the source water, have an impact on the O&M cost (bed life), they are generally minor factors in system design and equipment. One exception was pH, whereas all AM vendors recommended pH adjustment (equipment) when the pH exceeded 9.

For the very small AM systems, the highest cost system (\$228,309), with a design flow rate of only 40 gpm, had pH adjustment, backwash recycle, and extensive instrumentation accounting for the higher than expected total capital costs. The second highest cost AM system (\$166,050) had a very high EBCT (16 min), SS tanks, and two pH control systems for raw and treated water. For the most part, the low-cost systems had small EBCTs (1.5–3 min), used small, inexpensive polyglass tanks and had no backwash capability, automatic controls, or pH adjustment. The wide variation in costs of the very small systems is consistent with the cost data reported by Hilkert *et al.* (2010) on AM systems in California.

The total capital costs data shown in Figure 5(a) (flows $\geq$ 100 gpm) show less variation for the AM systems that is attributed to the majority of these systems having similar design features. The AM systems were mainly E33 media systems of parallel design with (FRP) tank systems having EBCTs around 5 min. The designs of the other systems (IR, C/F, and IX) were somewhat similar to the AM

Table 2 | Capital costs and design information of adsorptive media systems

				Media	Tanks							Equipment		Engineering		I & SSU[a]	
No.	ID	Year	Design flow gpm (L/min)	EBCT	Design	No.	Tanks material	EBCT min	pH system	Total capital cost ($)	$/gpm design flow	Cost ($)	%	Cost ($)	%	Cost ($)	%
1	BL	2005	10 (38)	ARM 200	Series	2	FRP	3.4	No	27,255	2,726	10,435	38	11,000	40	5,820	21
2	GF	2004	10 (38)	E33	Series	2	FRP	3.7	No	34,201	3,420	22,431	66	4,860	14	6,910	20
3	SU	2005	12 (45)	A/I Complex	Series	3	Polyglass	1.0	No	16,930	1,411	8,640	51	3,400	20	4,890	29
4	WA	2004	14 (53)	A/I Complex	Series (2)	6	Polyglass	1.6	No	16,475	1,177	10,790	65	1,800	11	3,885	24
5	PF	2008	15 (57)	ArsenX^{np}	Series	2	FRP	1.1	No	17,255	1,150	11,345	66	[b]		5,910	34
6	WS	2008	20 (76)	Adsorbsia	Series	2	FRP	2.8	No	51,895	2,595	30,215	58	10,110	19	11,570	22
7	DM	2004	22 (83)	A/I Complex	Series (2)	6	Polyglass	1	No	14,000	636	8,990	64	2,400	17	2,610	19
8	KF(1)	2005	30 (114)	ArsenX^{np}	Series (2)	4	FRP	2.5	No	55,847	1,862	39,108	70	9,941	18	6,798	12
9	VV	2004	37 (140)	AAFS50	Series	2	FRP	3.5	Yes	228,309	6,171	122,544	54	50,659	22	55,106	24
10	BR	2005	40 (151)	E33	Series	2	CS	4.1	Yes	138,642	3,466	94,662	68	24,300	18	19,680	14
11	BW	2004	40 (151)	G2	Series	2	SS	16	Yes	166,050	4,151	105,350	63	17,200	10	43,500	26
12	RR	2004	45 (170)	E33	Series	2	FRP	3.7	No	88,307	1,962	63,785	72	11,372	12	13,150	15
13	LI	2005	50 (189)	ArsenX^{np}	Parallel	2	FRP	4.0	No	114,070	2,281	82,470	72	12,800	11	18,800	16
14	KF(2)	2005	60 (227)	ARM 200	Series	2	FRP	2.5	No	59,516	992	41,689	70	10,587	18	7,240	12
15	KF(3)	2005	60 (227)	Adsorbsia	Series	2	FRP	2.5	No	73,258	1,221	51,314	70	13,032	18	8,912	12
16	TN	2007	63 (238)	E33	Parallel	2	FRP	4.5	Yes	115,306	1,830	86,018	75	12,897	11	16,391	14
17	LD	2007	75 (283)	ArsenX^{np}	Series	2	FRP	2.8	No	87,892	1,172	60,678	69	14,214	16	13,000	15
18	WM	2006	100 (379)	E33	Parallel	2	CS	5.7	Yes	149,221	1,492	103,897	70	25,310	17	20,014	13
19	RF	2003	120 (454)	E33	Parallel	2	FRP	3.7	Yes	131,692	1,097	105,805	80	4,672	4	21,215	16
20	TE	2005	150 (568)	Isolux	Parallel	4	CS	0.6	No	76,840	512	58,500	76	8,500	11	9,840	13
21	AL	2005	150 (568)	E33	Series	2	FRP	3.1	No	179,750	1,198	124,103	69	14,000	8	41,647	23
22	NP	2006	160 (605)	E33	Parallel	2	FRP	3.3	Yes	143,113	894	116,645	82	11,683	8	14,830	10
23	GE	2007	200 (757)	E33	Parallel	2	CS	3.7	No	139,149	696	101,290	73	19,545	14	18,314	13
24	SV	2004	3,000 (1,136)	E33	Parallel	2	FRP	4	No	211,000	703	129,500	61	36,700	17	44,800	21
25	AN	2003	320 (1,211)	E33	Parallel	2	FRP	3.6	No	153,000	478	112,000	73	23,000	15	18,000	12
26	RN	2005	350 (1,325)	GFH	Parallel	3	CS	5.2	No	232,147	663	157,647	68	16,000	7	58,500	25
27	TA	2005	450 (1,703)	E33	Parallel	3	FRP	3.6	No	296,644	659	202,685	68	32,750	11	61,209	21
28	BC	2003	640 (2,423)	E33	Parallel	4	FRP	3.7	No	305,000	477	218,000	71	35,500	12	51,500	17

$/gpm can be converted to $/L min using a multiplier factor of 0.264.

[a] Installation and system start-up.

[b] Included in equipment cost.

Table 3 | Capital costs and design information of iron removal, iron removal plus adsorptive media, coagulation/filtration, and ion exchange systems

					Filters						Equipment		Engineering		I & SSU[c]	
No.	Site ID	Year	Design flow rate gpm (L/min)	Contact tanks	No.	Material	Rate gpm/ft^{2}[a]	Filtration media	Total capital cost ($)	$/gpm design flow[b]	Cost ($)	%	Cost ($)	%	Cost ($)	%
IR																
1	SC	2005	20 (76)	2	4	FRP	5.4	Macrolite	63,547	3,177	20,227	35	20,227	32	12,410	22
2	DV	2005	45 (170)	1	2	FRP	9.4	Macrolite®	60,500	1,344	19,790	33	20,580	34	20,130	33
3	FC	2008	60 (227)	None	4	FRP	2.1	G2®	128,118	2,135	103,118	80	7,500	6	17,500	14
4	WV	2009	96 (363)	None	4	CS	3.4	GreensandPlus™	161,560	1,683	90,750	56	22,460	14	48,350	30
5	CM	2004	140 (530)	2	2	FRP	10	Macrolite®	270,530	1,932	159,419	59	39,344	15	71,767	27
6	SA	2006	250 (946)	2	2	FRP	10	Macrolite®	287,159	1,149	160,875	56	49,164	17	77,120	27
7	SD	2006	340 (1,287)	Yes	3 cells[d]	Al	2.5	Silica Sand	364,916	1,073	205,800	56	27,077	7	132,039	36
8	GV	2009	375 (1,420)	None	3	FRP	10	Macrolite®	332,584	887	196,542	59	48,057	14	87,985	26
9	PW	2005	400 (1,514)	1	2	CS	10	Macrolite®	334,573	836	224,994	67	30,929	9	78,650	24
10	AR	2006	770 (2,915)	1	2	CS	10	Macrolite®	427,407	555	281,048	66	50,770	12	95,589	22
IR/AM																
1	WL	2008	30 (114)	None	2	FRP	4.8	Birm®/ Filox™ + GTO	66,362	2,212	46,267	70	3,850	6	16,245	24
2	GS	2008	25 (95)	None	3	FRP	9	AD26 + E33	55,423	2,217	31,735	57	11,278	20	12,410	22
3	SF	2005	250 (946)	None	3	CS	6.1	AD26 + E33	292,252	1,169	212,826	73	27,527	9	51,899	18
4	ST	2006	250 (946)	Yes	4 cells[d]	CS/ RFP	2.6	Silica Sand + E33	367,838	1,471	273,873	74	16,520	4	77,445	21
C/F																
1	CL	2009	250 (946)	None	3	CS	5.2	AD GS^{+}	216,876	868	161,650	75	21,726	10	33,500	15
2	TF	2006	250 (946)	2	2	FRP	10	Macrolite®	305,447	1,222	168,142	55	53,534	17	83,870	27
3	FE	2006	375 (1,420)	2	3	FRP	10	Macrolite®	334,297	891	201,292	60	44,520	13	78,650	24
4	OK	2008	550 (2,082)	2	1	CS	10	Electromedia® I	424,817	772	296,430	70	48,332	11	80,055	19
IE																
1	FL	2005	250 (946)	NA	2	FRP	12.5	Purolite Arsenex II	286,388	1,146	173,195	61	35,616	12	77,574	27
2	VA	2006	540 (2,044)	NA	2	FRP	10	Purolite A300E	395,434	732	260,194	66	49,840	13	85,400	22

[a] gpm/ft^{2} can be converted to L/min/m^{2} by using a multiplier factor of 40.7.

[b] $/gpm can be converted to $/L/min by using a multiplier factor of 0.264.

[c] Installation and system start-up.

[d] Aeralater system.

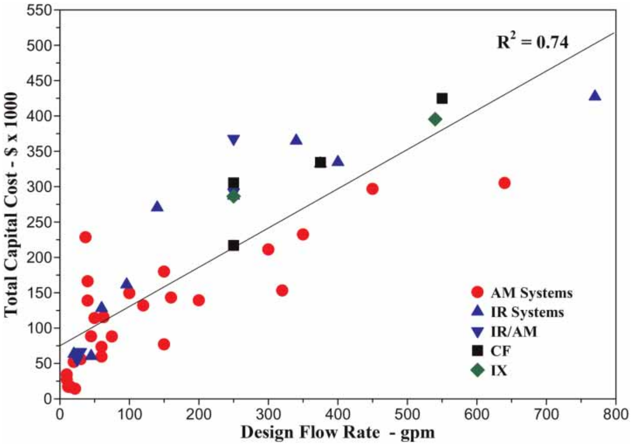

Figure 4 | Relationship between total capital cost of all treatment systems and design flow rate (gpm units can be converted to L/min by using a multiplier factor of 3.78).

systems consisting of parallel design (FRP) pressure filtration tank systems with comparable filtration rates.

As shown in Figure 5(a), the total capital costs of the AM systems treating ≥100 gpm were lower than those of other systems (shown as a group). The average cost on a \$/gpm basis for the AM systems was 21% lower than the IR/CF systems cost; \$806 versus \$1,019. The slightly higher capital cost of the IR, C/F, IR/AM, and IX systems is likely due to the additional ancillary equipment that include contact tanks (C/F systems) and the instrumentation and controls of these systems. This difference in cost is also consistent with the California systems cost data reported by Hilkert *et al.* (2010) where the IR and C/F systems had higher capital costs than the AM systems.

Equipment, engineering, and installation and start-up cost

A breakdown of the total capital costs into the three cost categories of equipment, engineering, and installation and start-up is provided in Tables 2 and 3. Except for two systems, the highest cost category for all of the systems was equipment. When broken down by types of system into two groups, AM and all other systems (Figure 6(a) and 6(b)), the average percent for the equipment costs for the two groups is 67 and 61%, respectively. Considering all of the systems as a whole, equipment cost amounted to around two-thirds of the total capital cost.

The second highest cost category was installation and start-up with the average percent for the AM system at 18% and the other systems group slightly higher at 24%. The engineering category averaged 15 and 14% for the AM and other systems, respectively.

Equipment cost proposals were solicited for each project in the ADP. Assuming that most small water systems would likely follow the same process of seeking cost proposals from equipment vendors for an arsenic treatment system, as a rule of thumb, the water system should expect the total capital cost (that included equipment, engineering, and installations and start-up) to be as follows:

$$\text{Total Capital Cost } (\$) \ = 1.5 \times \text{Equipment Cost } (\$)$$

Operational and maintenance cost

The O&M costs for 35 arsenic removal systems are provided in Table 4 (15 AM systems) and Table 5 (20 other systems). During the ADP evaluation studies, only 15 systems changed out the adsorptive media and thus the O&M cost data in Table 4 are limited to these 15 AM systems.

Figure 7 presents the O&M costs on a 1,000 gal (Kgal) (all Kgal and \$/Kgal units can be converted to LK and \$/KL by using a multiplier of 0.035) of treated water basis for all treatment systems by their design flow rate. As reported in Tables 4 and 5 and shown in Figure 7, the total O&M costs for the AM systems had a very wide range from \$0.61 to \$22.88 compared to a range of only \$0.07 to \$2.90 for the other systems. Moreover, if the three very high O&M costs (\$2.90, \$2.26, and \$1.93) of these non-AM systems are excluded, the cost range of the other 17 systems is only \$0.07–0.65 and the average is \$0.34/Kgal.

Unquestionably, the average O&M cost for the AM systems is substantially higher than the other types of systems, particularly for the very small systems (flows ≤100 gpm), as more clearly shown in Table 6. Furthermore, as shown in Table 6, the average unit O&M costs for all of the systems are significantly higher for the smaller size (≤100 gpm) systems than the larger systems (≥100 gpm).

The higher O&M costs of the AM systems are attributed to media replacement whose costs ranged from 49 to 97% of the total AM O&M costs with the average of all 15 systems

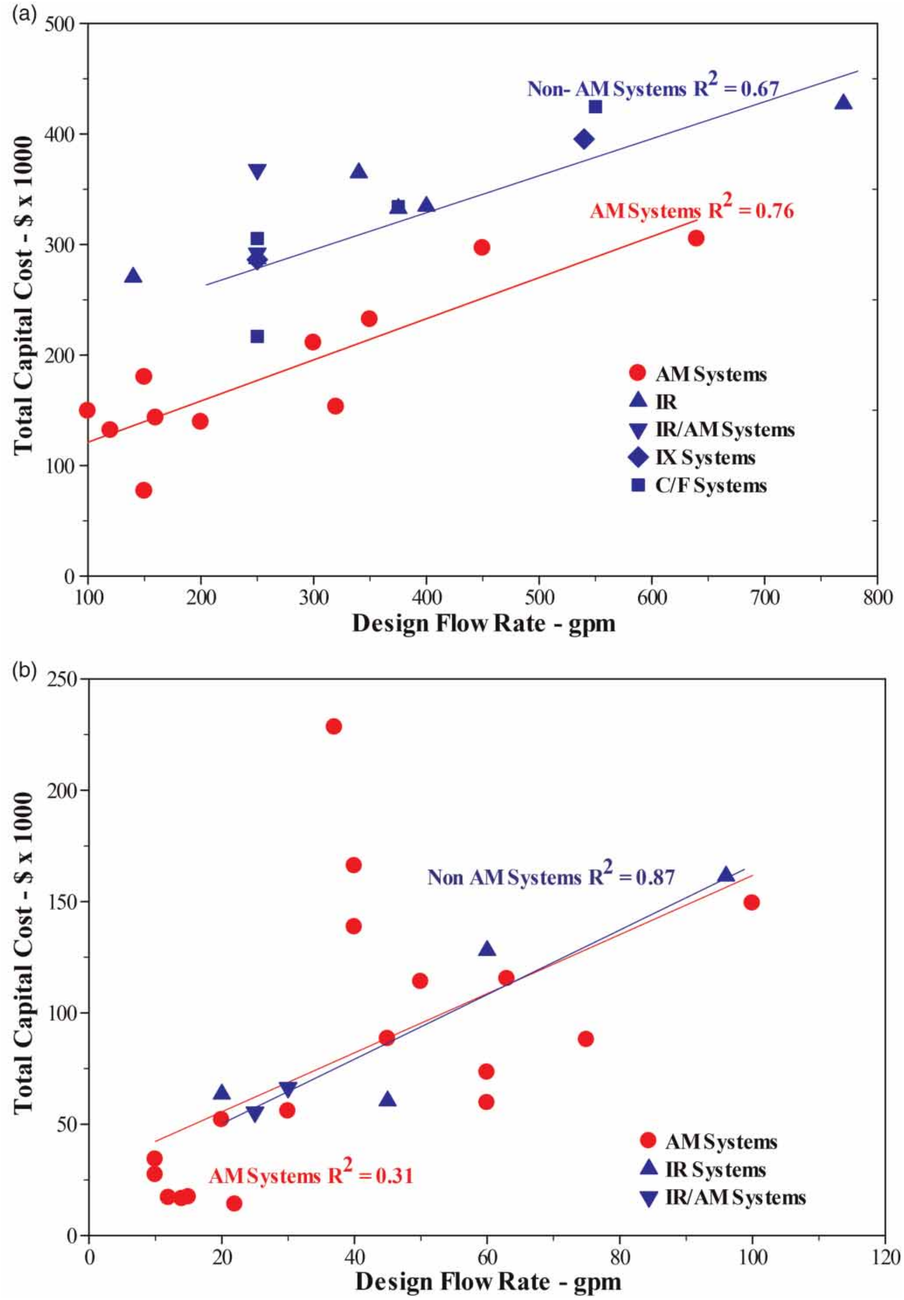

Figure 5 | Relationship of total capital cost of water systems and design flow rate by system category (gpm units can be converted to L/min by using a multiplier factor of 3.78).

at 81% (Tables 4 and 6). Media replacement cost is a function of the media cost and bed life (the number of bed volumes (BVs) of treated water before change out). Media products in the ADP ranged from around $80–595 per cubic feet and the number of BVs of water treated before change out ranged from a low of 3,064 to a high of 80,000 BVs. To clearly illustrate the impact of media life, the total O&M cost presented on BV of treated water is shown in Figure 8. The three highest O&M costs were for systems using high cost media products that had a very short bed life. Several systems achieved over 100,000 BVs of treated water, but because the media was not changed out during

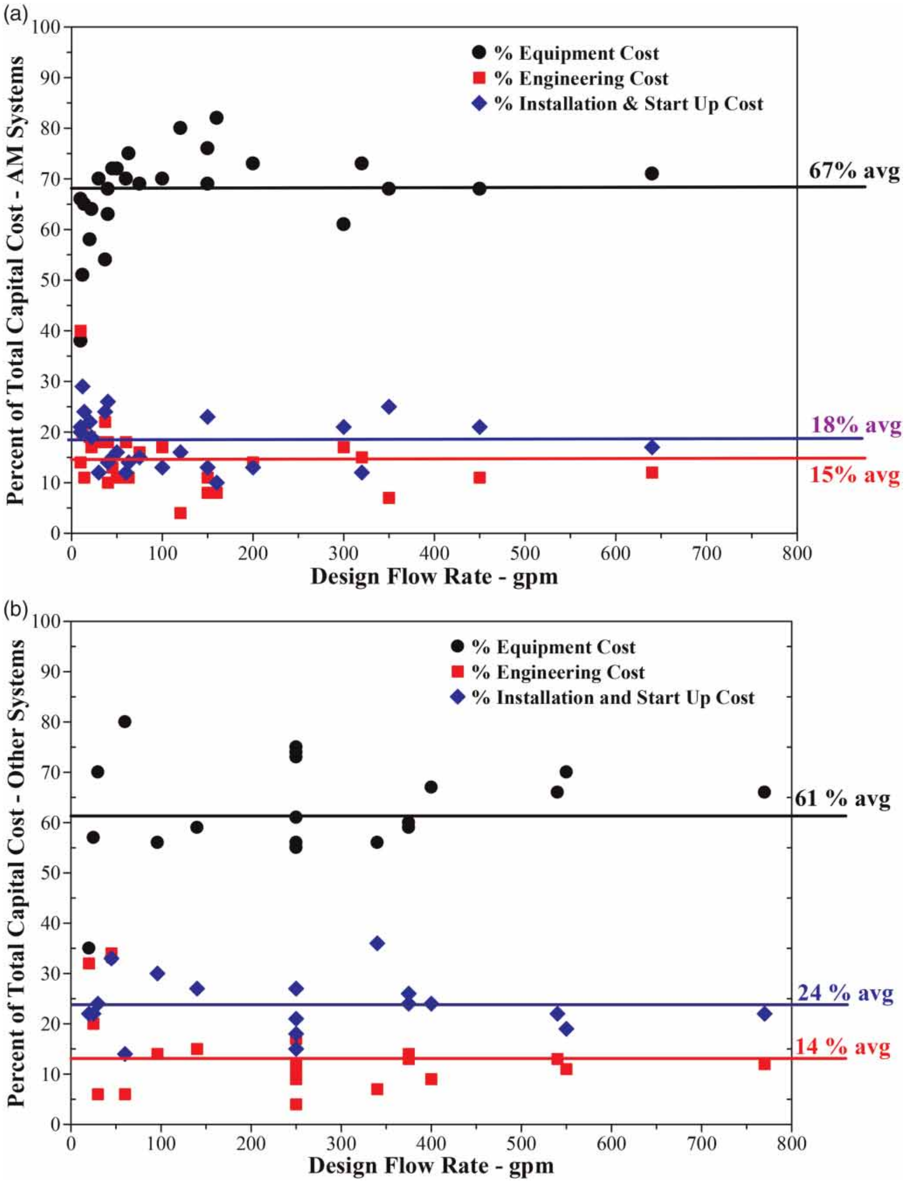

Figure 6 | Percentage of three cost categories of the total capital costs of adsorptive media systems and other systems (gpm units can be converted to L/min by using a multiplier factor of 3.78).

the ADP studies, their O&M costs are not included in the data set. The O&M cost for these systems would likely be less than the costs of systems treating 80,000 BVs.

At two sites (WA and VV sites), the adsorptive media were changed out three times with the objective to lower the O&M cost. At the WA site, each change resulted in a lower O/M cost mainly the result of increased bed life (Figure 9). At the VV site, pH adjustment was found to lower the media cost by extending the bed life of the original AA media by about 12%. However, the change to a higher performing media product and without pH adjustment did not reduce the O&M cost because of the significantly higher media cost (Figure 9).

Labor was the highest cost category for the IR (65%) and C/F (66%) systems and the second highest cost category for the AM (16%) and the IX systems (9%). Labor cost reported on a unit basis of $/Kgal of treated water is a function of the operator's time and salary and the amount of water

Table 4 | Operational and maintenance cost of adsorptive media systems

						Media[b]			**Chemicals**			**Labor**	
No.[a]	**Site ID**	**Design flow rate L/min**	**Media**	**BVs to break through × 1000**	**Total O/M cost $/Kgal**	**Cost $/Kgal**	**% of total O/M**	**Electricity $/Kgal**	**Type**	**Cost $/Kgal**	**Avg weekly hours**	**Labor rates $/hr**	**Cost $/Kgal**
2	GF	10 (38)	E33	27,874	2.34	2.01	86	0.00	None	0.00	0.5	21.00	0.33
3	SU	12 (45)	A/I Complex	7,660	12.06	8.96	74	0.00	None	0.00	0.33	30.00	3.10
4	WA	14 (53)	A/I Complex	5,100	22.88	22.05	96	0.00	None	0.00	0.75	20.00	0.83
4	WA	14 (53)	GFH	11,600	10.44	9.44	90	0.00	None	0.00	0.75	20.00	1.00
4	WA	14 (53)	CFH	15,300	5.52	4.76	86	0.00	None	0.00	0.75	20.00	0.76
5	PF	15 (57)	LayneRT	15,000	7.67	5.31	69	0.00	None	0.00	1.6	20.00	2.36
7	DM	22 (83)	A/I Complex	5,814	10.86	9.99	92	0.00	None	0.00	0.5	20.00	0.87
9	VV	37 (140)	AAFS50	10,364	2.74	2.56	93	0.16	None	0.00	0.4	21.00	0.03
9	VV	37 (140)	AAFS50	23,031	2.06	1.15	56	0.16	Acid	0.61	2.4	21.00	0.14
9	VV	37 (140)	ARM 200	25,717	3.40	3.32	98	0.16	None	0.00	0.4	21.00	0.03
11	BW	40 (151)	G2®	3,064	5.11	4.30	84	0.00	Acid/base	0.11/0.36	2.33	20.00	0.34
12	RR	45 (170)	E33	52,151	0.86	0.64	74	0.01	None	0.00	1.67	21.00	0.22
14	KF	60 (227)	ARM 200	13,940	5.82	5.37	92	0.00	None	0.00	2.5	21.00	0.45
17	LD	75 (283)	ArsenX^{np}	66,794	0.98	0.58	59	0.00	None	0.00	7	21.00	0.40
20	TE	150 (568)	Isolux™	80,000	1.16	1.02	88	0.00	None	0.00	2.5	37.50	0.14
21	AL	150 (568)	E33	38,140	0.61	0.36	59	0.00	None	0.00	4.67	19.50	0.25
24	SV	300 (1,136)	E33	78,393	0.61	0.30	49	0.05	Replacement parts	0.03	1.75	21.80	0.23
25	AN	320 (1,211)	E33	50,191	0.75	0.66	89	0.00	Replacement parts	0.03	1.75	18.20	0.05
26	RN	350 (1,325)	GFH®	7,200	5.69	5.51	97	0.00	None	0.00	2.5	35.00	0.18

[a] Reference number; see Table 2.

[b] Media changed out of all tanks of both series and parallel design systems.

Table 5 | Operational and maintenance cost of iron removal, iron removal plus adsorptive media, coagulation/filtration, and ion exchange systems

				Chemicals			**Electricity**		**Labor**			
No.	**Site ID**	**Design flow rate gpm (L/min)**	**Total O&M costs ($/Kgal)**	**Type**	**Cost ($/Kgal)[a]**	**% of total O&M**	**Cost ($/Kgal)[a]**	**% of total O&M**	**Average weekly hours**	**Labor rate ($/hr)**	**Cost ($/Kgal)[a]**	**% of total O&M**
IR												
1	SC	20 (76)	0.36	$KMnO_4$	$0.07	19	0.01	3	0.42	21.00	0.28	78
2	DV	45 (170)	0.26	NaClO	$0.09	34	0.06	24	0.42	10.80	0.11	42
3	FC	60 (227)	2.26	NaClO	$0.00	0	0.00	0	1.67	22.00	2.26	100
4	WV	96 (363)	0.65	$NaMnO_4$	$0.37	57	0.16	25	1.75	15.00	0.12	18
5	CM	140 (530)	0.29	$FeCl_3$[b]	$0.03	10	0.04	14	2.5	21.00	0.22	76
6	SA	250 (946)	0.43	NaClO	$0.05	12	0.01	2	1.75	10.00	0.37	86
7	SD	340 (1,287)	0.27	NaClO	$0.04	15	0.16	59	4.5	18.00	0.07	26
8	GV	375 (1,420)	0.55	NaClO	$0.00	0	0.03	5	10	24.00	0.52	95
9	PW	400 (1,514)	0.17	$FeCl_3$[b]	$0.01	8	0.05	29	2.5	30.00	0.11	64
10	AR	770 (2,915)	0.07	$KMnO_4$	$0.03	43	0.00	0	2.5	$30.00	0.04	57
IR + AM												
1	WL	30 (114)	1.93[b]	None	$0.00	0	0.39	20	3	30.0	1.54	80
2	GS	25 (95)	2.90[b]	NaClO	$0.33	11	0.00	0	1.6	16.0	2.57	89
3	SF	250 (946)	0.33[b]	NaClO	$0.17	51	0.00	0	2.33	21.0	0.16	48
4	ST	250 (946)	0.16[b]	NaClO	$0.00	0	0.08	50	1.7	16.3	0.08	50
C/F												
1	CL	250 (946)	0.46	$FeCl_3$	$0.07	15	0.06	13	6	22.0	0.33	72
2	TF	250 (946)	0.18	$FeCl_3$	$0.02	9	0.01	3	4.7	19.6	0.16	88
3	FE	375 (1,420)	0.31	$FeCl_3$	$0.05	16	0.05	15	5.25	30.0	0.21	69
4	OK	550 (2,082)	0.18	$FeCl_3$, NaClO	$0.03, $0.01	17	0.08	44	5.25	30.0	0.06	33
IE												
1	FL	250 (946)	0.62	Salt	$0.49	79	0.08	13	2.5	21.00	0.05	8
2	VA	540 (2,044)	0.35	Salt	$0.29	83	0.03	8	3.3	21.00	0.03	10

[a] $/Kgal can be converted to $/KL by using a multiplier factor of 3.78.

[b] Iron addition to increase arsenic removal.

Media replacement cost not incurred during the study period; thus, not included in the total O&M cost.

produced by the water treatment system. A review of the operator time records found that the average time, hours per week, spent by the operator average 2.1 hours for the AM systems and slightly higher at 3.2 hours for the other systems.

Labor rates ranged from $10 to $37.50/hour with the average being $22/hour. Thus, with weekly labor cost (operator hours × operator rate) being a fixed cost, the unit O/M labor cost is dependent on the amount of treated water produced during a week. Surprisingly, the systems utilization rates (percentage of time system treating water) were very low, less than 50%, except for one system (Figure 10). By increasing the production time of the systems, the unit labor cost could be lowered. However, the amount of treated water produced is dependent on water demand. If and when a system's water demand is increased, the labor cost on a unit basis will decrease. Because the labor cost is only around 16% of the total AM systems O&M costs, increasing water production for the AM systems would have only a small impact on the total O&M cost.

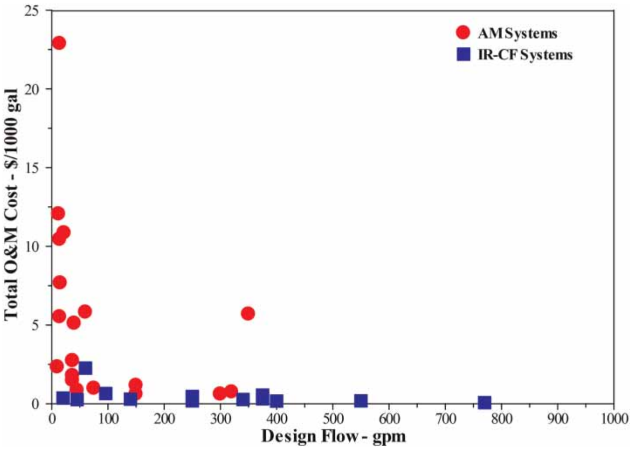

Figure 7 | Total O/M cost verses system design flow of all systems (gpm units can be converted to L/min by using a multiplier factor of 3.78; $/1,000 gal can be converted to $/1,000 L by using a multiplier factor of 3.78).

The only treatment systems that had significant chemical costs were the two IX systems (salt for regeneration) and three AM system that required pH adjustment (Tables 4 and 5). Electrical costs were also very low with only five systems reporting power costs greater than $0.08/Kgal.

The lower O&M cost is a significant advantage of IR/CF over AM as long as the facility is able to handle the residual disposal at a low cost. All of the IR and CF systems in the ADP had access to sewers and, therefore, residual disposal was not a significant cost issue. Although the cost of residual disposal for the ADP systems was not included in the O&M cost and was not an issue for these systems, residual disposal could be a significant cost issue depending on local conditions and State regulations and must be considered in the technology selection process.

CONCLUSIONS

The review of the cost capital and O&M data compiled from the EPA Arsenic Demonstration Program has led to the following conclusions.

Capital cost

(1) Many factors affect the total cost of an arsenic treatment system that include system flow rate, vessel design and material, media type and quantity, pre- and/or post-treatment requirements, level of instrumentation and controls, and site-specific conditions.

(2) Because of the wide variation in designs of the smaller (≤100 gpm) AM systems, the equipment costs of these systems can vary significantly for the same size system.

(3) The designs of the larger (≥100 gpm) AM systems were found to be somewhat similar and, therefore, the equipment costs of the systems had less variation for the same type and size of systems.

(4) For the larger (≥100 gpm) systems, the average cost ($/gpm) for the AM systems was found to be 21% lower than those for the IR, C/F, and IX systems. The reason for the slightly more expensive IR, C/F, and IX systems was due to the extra ancillary equipment and controls, such as contact tanks, iron addition system, and brine tanks associated with these systems.

(5) A breakdown of the total capital cost into three categories (equipment, engineering, and installations and start-up cost) found the equipment cost to be the major component of all treatment systems and amounts to approximately two-thirds of the total capital cost.

Table 6 | Summary of the operational and maintenance cost of arsenic removal systems

Technology	Total O&M (Avg) ($/Kgal)[a]	Media replacement cost ($/Kgal)[a]	Chemical cost ($/Kgal)[a]	Electricity cost ($/Kgal)[a]	Labor cost ($/Kgal)[a]
Systems <100 gpm (379 L/min)					
AM	6.47	5.58	0.08	0.03	0.78
IR and CF	1.39	NA	0.14	0.10	1.15
Systems > =100 gpm (379 L/min)					
AM	1.76	1.57	0.01	0.01	0.17
IR and CF	0.28	NA	0.04	0.05	0.19
IX	0.49	NA	0.39	0.06	0.04

[a] $/Kgal can be converted to $/KL by using a multiplier factor of 3.78.

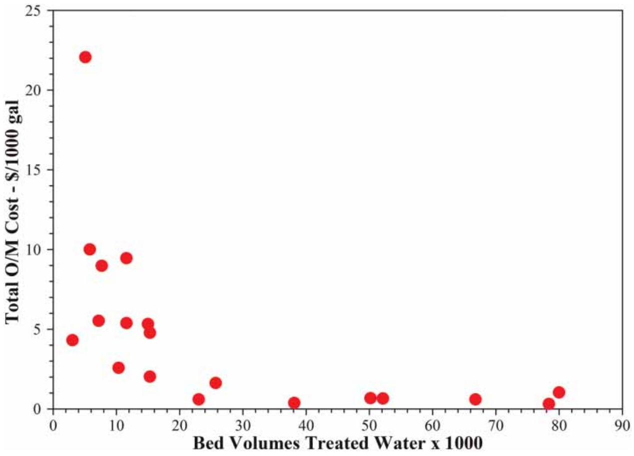

Figure 8 | Relationship between AM O/M cost and BVs of treated water ($/1,000 gal can be converted to $/1,000 L by using a multiplier factor of 3.78).

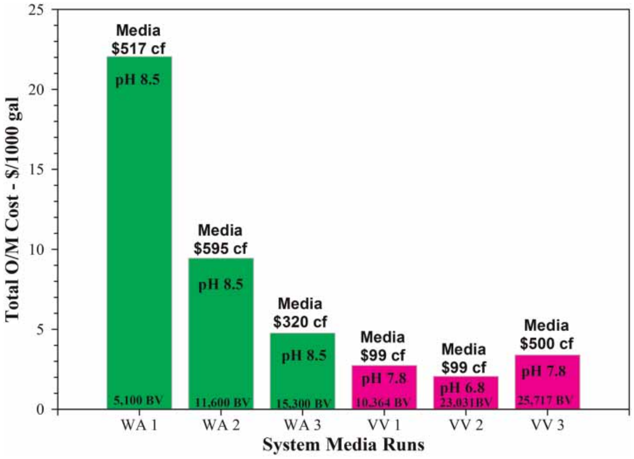

Figure 9 | Impact of media and pH adjustment on total O/M cost ($/1,000 gal can be converted to $/1,000 L by using a multiplier factor of 3.78; $/cf can be converted to $/L by using a multiplier factor of 0.035).

(6) A rough estimate of the total capital cost using an equipment vendor's estimated system cost can be made by increasing the estimated equipment cost by 50%.

O&M cost

(1) AM systems have significantly higher O&M costs than all other treatment systems because of the need to replace the adsorptive media when exhausted for arsenic removal.

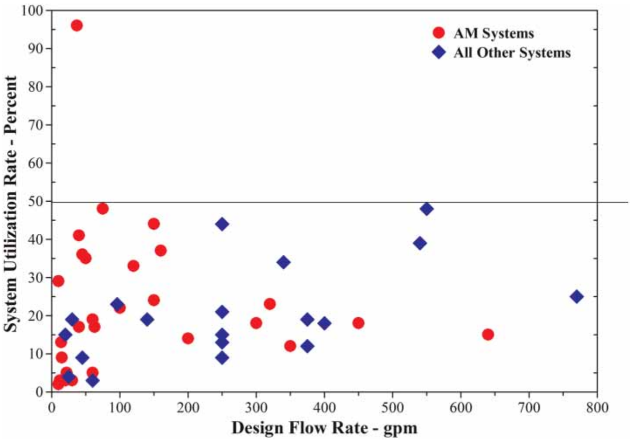

Figure 10 | Relationship of system utilization rate to design flow rate of all systems (gpm units can be converted to L/min by using a multiplier factor of 3.78).

(2) For AM systems, media replacement amounts to around 80% of the total O&M cost.

(3) AM systems can reduce the O&M cost by replacing the existing media with a lower cost media of equal performance or a media of the same cost, but having a higher arsenic removal capacity. Replacing the existing media project that has the combination of low unit cost and longer bed life provides the lowest O&M cost reduction.

(4) AM systems, except for those designed with very short EBCTs, can reduce their O&M cost by easily converting the system over to a C/F system providing that the backwash water can be easily disposed of. The conversion process will require some capital cost investment in a chemical feed system and a filtration media.

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