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Article 3: Cost Benefits of Point-Of-Use Devices in Reduction of Health Risks from Drinking Water

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[Edited for clarity]

1.0 Introduction

Since the passage of the Safe Drinking Water Act in 1974 the United States Environmental Protection Agency (USEPA) has been responsible for the development of standards to limit the exposure of harmful substances via drinking water. There are two types of standards. Primary standards regulate substances harmful to human health and secondary standards address substances related more to aesthetics. Maximum Contaminant Level (MCL) refers to the maximum concentration of a harmful substance designed to protect human health allowed in the drinking water. Achievement of the MCL does not mean that no risk exists, but that it has been reduced to a very low level. [For potential carcinogens] risk estimates […] always [have] a level of uncertainty because they are often derived from studies based on animals- primarily mice and rats- and the need to extrapolate probability of cancer to very low levels of exposure via drinking water to humans. To compensate for this uncertainty safety factors are used extensively.

Contaminants are any physical, chemical, biological or radiological substances or matter in water. The Maximum Contaminant Level Goal (MCLG) is the level at or below which there are no known adverse effects to all humans. MCLG is often zero for many chemicals based on existing studies and interpretations.

1.1 Why treatment at the tap?

There are a number of reasons why treatment at the tap has potential additional health benefits (Table 1). The additional removal of contaminants below the MCL will result in further lowering the risk from exposure to potentially harmful substances, thus lowering the risk of an adverse health outcome. This aids in reducing the uncertainty used in risk estimates. Assessing the potential health effects is a continuing effort by regulatory agencies as new data becomes available.

Table 1. Why treatment at the tap?

Additional reduction of risk	Reduction of risk below MCL from that level or occasional higher levels that may occur due to treatment deficiencies or excursions to higher levels from averages. This further reduces uncertainty and provides additional protection
Protection from unknown/unregulated contaminants	Additional contaminants are likely to be regulated in the future as better data becomes
Protection from contamination in the distribution system	Contamination post-municipal treatment before or after household delivery
Use of untreated water sources	Use of untreated groundwater by domestic individual homeowners or systems not regulated by government agencies
Aesthetic concerns or preferences	Improved taste or smell from municipal or untreated waters

1.1.1 Additional reduction of risk

Reducing risk below an MCL from that level or occasional higher levels that may occur due to treatment deficiencies or excursions to higher levels from averages is possible with treatment at the tap. Point-of-Use (POU) devices may provide the consumer with an additional protection and lower the risk further from any adverse health effects. This also helps reduce uncertainty that is inherent in any risk assessment used to set an MCL.

1.1.2 Protection from unknown contaminants

The USEPA reviews potential regulation of additional contaminants in drinking water as new information becomes available on a five-year cycle. These include both chemical and microbial contaminants. Current technologies used to treat water at the tap are capable of dealing with contaminants likely to be regulated in the future.

1.1.3 Protection from contamination in the distribution system

The delivery of water to facilities/homes usually requires transport through many miles of pipe. Although the water may have been treated it is subject to recontamination during travel through the utility distribution system and the piping system within a home or facility. Illicit connections and cracks in utility distribution systems occur, allowing the potential for contaminants to enter the distribution system. In addition, it has been shown that routine repair and maintenance of the distribution system can result in contamination of the drinking water.

The additional protection allotted from POU devices is important for sensitive populations where exposures to drinking water contaminants are more likely to result in adverse health outcomes including increased mortality. These populations include newborns, children, pregnant mothers, immunocompromised individuals, and the elderly.

1.1.4 Individual drinking water wells

Domestic wells in the US are unregulated and their owners are often unaware of the chemical and microbial quality of their drinking water. Privately owned wells are less likely to be routinely monitored and treated. Results indicated that domestic well users accounted for 12% of the US population or 37.7 million persons (Kumar et al., 2010). Domestic wells are usually shallower than public and more susceptible to contamination from surface waters (Kumar et al., 2010). In addition domestic wells may be more susceptible to contamination from natural deposits of minerals such as arsenic, radon, uranium, and nitrates.

1.1.5 Cost of POU/POE devices

There are many options for treating drinking water at the point-of-use (POU) and each approach has unique capabilities and associated costs. A brief list of POU types, associated costs, and certified removal capabilities are described in Table 2 and Table 3. Using a simple POU calculator (http://www.cyber- nook.com/chart/default.asp), over a five year period there was not a large difference in costs between reverse osmosis ($680), activated carbon filtration ($546), and pour-through filtration units ($645). UV treatment (POE) ($1,499), adsorptive media ($936), and distillation ($740) were nearly twice as expensive over the 5 year cost of operations. Ion exchange (POE) ($1,870) was the most expensive option over 5 years.

Table 2. Point-of-use/point-of-entry devices and associated costs

POU/POE	**Initial cost**	**Operation and maintenance cost (per year)**	**5 year total cost ***	**Annual cost over 5 years ****	**Lifetime unit cost (70 years) *****	**Reference**
No treatment	$0	$0	$0	$0	$0	-
Reverse Osmosis	$300	$95	$680	$136	$9,520	(Johnson, 2014; NSF International, 2015; USEPA,
Activated Carbon	$30	$129	$546	$109	$7,644	(NSF International, 2015; USEPA, 2006)
UV treatment	$1,059	$110	$1,499	$300	$20,986	(NSF International, 2015; USEPA, 2006)
Adsorptive Media	$520	$104	$936	$187	$13,104	(NSF International, 2015; USEPA, 2006)
Pour-through granular activated carbon pitcher filter	$25	$155	$645	$129	$9,030	(Harrison, 1999; Johnson, 2014; NSF International, 2015)
Distillation	$340	$100	$740	$148	$10,360	(Harrison, 1999; Johnson, 2014; NSF International,
Ion Exchange (softener)	$1,150	$180	$1,870	$374	$26,180	(Harrison, 1999; NSF International, 2015; Sargent-Michaud et al., 2007)

*5 year cost based on the initial cost plus annual costs for four additional years and assuming on the sixth year, the unit is completely replaced and thus a cost equal to the initial cost is required again. Costs based on data from http://www.cyber-nook.com/chart/default.asp?Usage=10&Years=4 (accessed May 9, 2016)

** 5 year cost divided by 5 years

*** Annual cost over 5 years times 70 years

Table 3. American National Standards Institute (ANSI) and National Sanitation Foundation (NSF) approved point-of-use/point-of-entry device removal claims

POU/POE	ANSI/NSF Standard number and reduction claim	Reference
Reverse Osmosis	Arsenic, Chromium, Nitrates, Lead (58) Protozoa*	(Johnson, 2014; NSF International, 2015; USEPA, 2006)
Activated Carbon	Bacteria and protozoa, Lead (53)*	(NSF International, 2015; United States Environmental Protection Agency,
UV treatment	Bacteria, viruses, Protozoa	(NSF International, 2015; USEPA,
Adsorptive Media	Arsenic (53)	(NSF International, 2015; USEPA,
Pour-through granular activated carbon pitcher filte	Chlorine, taste, odor and particulates (42)	(Harrison, 1999; Johnson, 2014; NSI International, 2015)
Distillation	Total arsenic, chromium, mercury, nitrate/nitrite and (62) Bacteria, viruses,	(Harrison, 1999; Johnson, 2014; NS International, 2015)
Ion Exchange (softener)	Hardness, barium, radium (44)	(Harrison, 1999; NSF International 2015;

* Microorganism contamination reduction claim under NSF P231 or USEPA Purifier Guide Standard. POU devices are required to 'remove, kill or inactivate all types of pathogenic organisms' at the following rates: Bacteria: 6 Log; Viruses: 4 Log; Protozoan cysts: 3 Log

[…]

3.0 Inorganic contaminants

There are many drinking water contaminants of concern regulated by USEPA and most of [their levels] can also be reduced by POU treatment systems ("WQA Technical Fact Sheet: Lead," 2013). We discuss a few of the well-studied contaminants (e.g. arsenic, nitrates, lead, and chromium) in the following sections.

3.1 Arsenic

Arsenic is a naturally occurring element widely distributed in the earth's crust. Its occurrence in water largely results from its release from natural deposits. It was previously used in pesticides, as a preservative, and other manufactured products. Two forms of arsenic are common in natural waters: arsenite (AsO_3^{3-}) and arsenate (AsO_4^{3-}), referred to as arsenic (III) and arsenic (V), respectively.

Arsenic has been associated with various types of cancer (skin, lung and urinary bladder) and non-cancer health effects, such as skin lesions, cardiovascular, pulmonary, immunological, neurological, and endocrine (e.g., diabetes) effects. The MCL for arsenic is 10 µg/L and is based on chemical toxicity rather than carcinogenicity (USEPA, 2013). Arsenic associated cancer prevalence and mortality rates in the United States are unknown (USEPA, IRIS 1998). Kurttio et al., (1999) conducted a case-cohort design study of 61 bladder and 49 kidney cancer cases and 275 controls to evaluate the risk of these diseases with respect to arsenic drinking water concentrations. In this study the median exposure was 0.1 µg/L, the maximum reported was 64 µg/L, and 1% of the exposure was greater than 10 µg/L. The authors reported that very low concentrations of arsenic in drinking water were significantly associated with bladder cancer when exposure occurred two to nine years prior to diagnosis.

3.1.1 Occurrence in water

Arsenic exposure largely results from groundwater sources. Welch et al., (2000) found that nearly half of the 30,000 arsenic analyses from groundwater, recorded in the U.S. Geological Survey's National Water Information System (NWIS) and other agency databases, were ≤1 µg/L and 10% exceeded 10 µg/L. The authors also reported that arsenic concentrations exceeding 10 µg/L appear to be more frequently found in the western states than in the eastern states.

[…]

In general, [groundwater provided by] public wells [has] less arsenic compared to domestic wells because the municipal water is treated (Peters et al., 1999). […A review of arsenic concentration in groundwater in various regions of the US demonstrated that the concentration remains unchanged over time.] With this assumption, this data can be applied for any time period in the past and can be extended to apply in the future.

Analysis of variance (ANOVA) […] showed that there was a significant statistical difference between regions ($p < 0.005$, $\alpha = 0.05$). This indicates that regional classification is essential when considering concentrations of arsenic in groundwater.

[…] Kumar et al. pointed out that while private domestic wells account for only 12% of the United State population, they represent 29% of the overall exposure to arsenic when the 10 µg/L limit is met by public water. [(Kumar et al., 2010)]

3.1.2 Groundwater arsenic risk assessment deterministic modeling

Arsenic concentration in groundwater (Table 9) reflects the regional concentrations at both public and rural wells before treatment. The USEPA recommends a maximum contamination level (MCL) of 10 µg/L. Public water treatment plants are required to remove arsenic in drinking water to at or below this level. Frey and Edwards (1997) reported regional percent arsenic removal at public water treatment plants (Table 10) ranged from 12-44%. Additionally, a recent study focused on a small community in the Southwestern United States found that POU devices removed up to 99% of arsenic concentrations (Lothrop et al., 2015). [Arsenic in this study was primarily in the pentavalent form.]

Table 9. Average concentration of arsenic in U.S. wells by region

	All U.S. Regions	New England	Mid-Atlantic	Southeast	Midwest	South Central	North Central	West
Dataset Start Date	1991	1991	1994	1995	1994	1992	1994	1991
Dataset End Date	2014	2014	2014	2014	2014	2014	2014	2014
Sample size (*n*)	7219	541	479	760	1143	1909	140	2247
Minimum (µg/L)	0.022	0.027	0.025	0.022	0.031	0.026	0.093	0.034
Average (µg/L)	3.88	2.10	1.55	1.54	4.08	3.46	3.39	4.90
Maximum (µg/L)	130	73	73	68	128	61	49	54
95% Upper CI*	4.08	2.62	1.95	1.84	4.67	3.70	4.56	5.37
95% Lower CI*	3.69	1.58	1.15	1.24	3.50	3.21	2.23	4.43
Standard Deviation	8.6	6.2	4.5	4.2	10.1	5.4	7.0	11.3
Standard Error	0.1	0.3	0.2	0.2	0.3	0.1	0.6	0.2

*CI: Confidence Interval

[The researchers determined the cost effectiveness of POU treatment technologies for arsenic by reviewing the following parameters for bladder cancer:

- The potential number of cancer cases associated with arsenic over the current population of the US
- The associated cost of medical treatment
- The drinking water arsenic concentration reduction possible with POU technologies
- The reduction in cancer rates and associated medical costs
- The cost of ownership of the POU treatment system over a 70 year lifetime…]

The greatest cancer risk reduction from POU devices occurs in rural areas where untreated well water leads to higher exposures of arsenic concentrations. More specifically, risk reduction is greatest in rural wells in the Midwest, West, South Central, and North Central U.S. regions. For public water supplies, the only significant reduction in risk appears to be in the West where arsenic concentrations are the greatest. Figure 1 shows the lifetime cancer risk for arsenic concentrations in drinking water found in the U.S. between 1991and 2014.

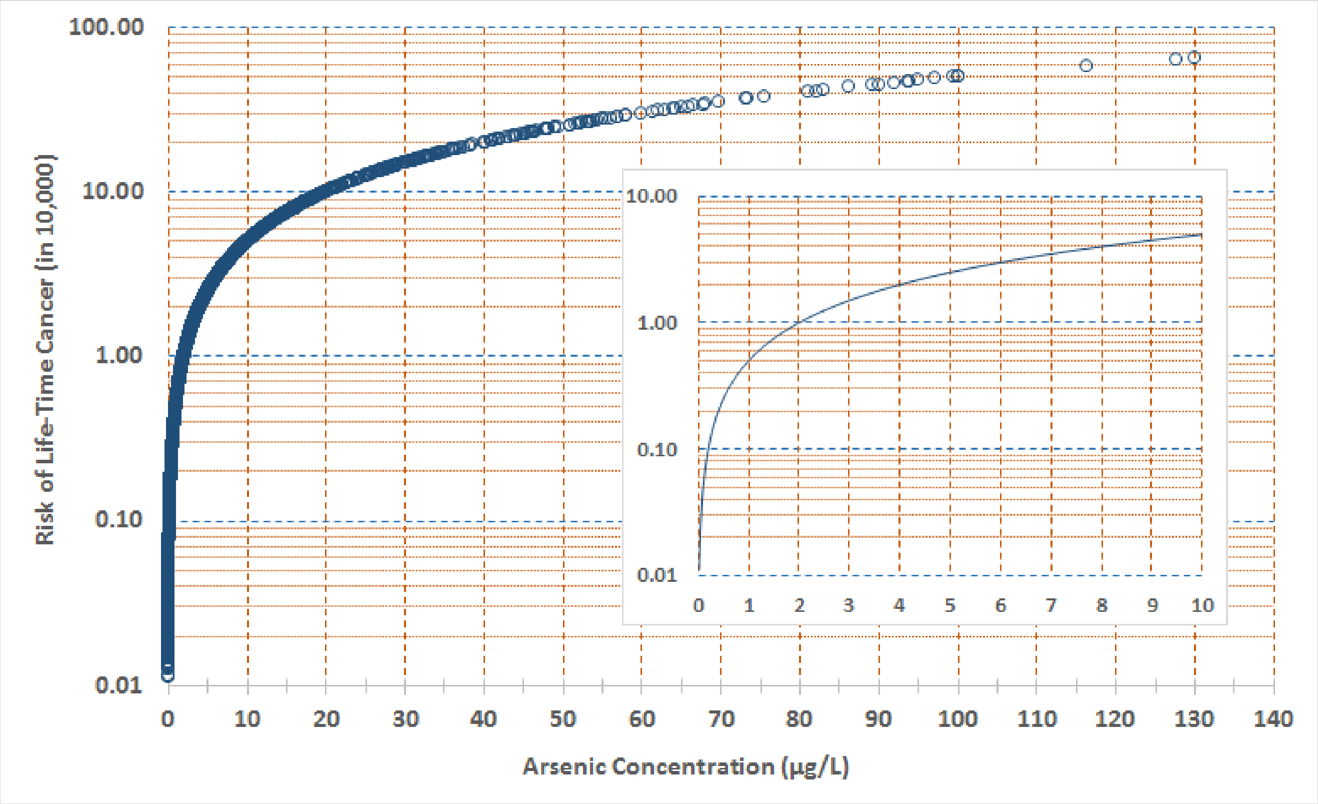

Figure 1. Risk of lifetime cancer vs. arsenic concentration in drinking water

3.1.4 Discussion of POU devices to remove arsenic

The ability for POU devices to remove arsenic in water depends on many variables including pH and redox potential which control arsenic speciation and thus drive treatment options. Activated carbon has been studied extensively for arsenic removal (Mohan and Pittman, 2007), but carbon only removes a few milligrams of metal ions per gram of activated carbon. Other popular treatment options include reverse osmosis, adsorptive media (e.g. iron based media and alumina), and distillation. A summary of common

POU treatment devices and reported arsenic removing capabilities are described in Table 13.

3.1.5 Cost-effectiveness analysis for arsenic in drinking water

Calculating the cost-benefit of a POU intervention includes the cost of the POU (initial investment plus maintenance and unit replacement projections) compared to savings due to averted costs of disease burden. Diseases related to arsenic where cost estimates are available include bladder, skin (nonmelanoma), and lung cancers. Table 14 lists medical costs, estimated arsenic associated cases per year and the total annual cost estimate for each disease along with cumulative yearly expenses. The annual population cost of arsenic related cancer (bladder, skin and lung) is $1.6B. However, for the cost-effectiveness calculations in this study, we assumed only bladder cancer response to arsenic exposure through drinking water as the other adverse health outcomes (skin and liver cancers) are associated with inhalation and dermal exposure of arsenic contaminated water, not ingestion of contaminated drinking water.

[…] The cost (USD) per unit risk reduction was defined for each POU device (Table 15). Cancer rates are not linear with relation to arsenic exposure and thus an annual cost-effectiveness value was not derived. This calculation assumes the device is used routinely for 70 years and each POU device has a 5 year lifetime then is replaced for the initial unit cost. The cost-effectiveness details for each POU device are presented in Table 15. Distillation is capable of the largest reduction in lifetime cancer risks (1.50 cases in 10,000 individuals) while adsorptive media is the most cost-effective when compared to the other approved POU devices.

[…] The cost of no intervention was calculated to be $61,054. This value is based on the discounted cost of medical treatment for arsenic-associated bladder cancer after 30 years and a 12 month compound interest cycle of 3% at $150,000 in 2015 (Present Value of Lump Sum calculation). This cost does not account for mortality, adjusted life years, quality of life losses, or inflation since these values are currently unknown but could be assumed with acknowledgement of uncertainty. Risk reduction input parameters vary by POU intervention type and risk reduction with no intervention is assumed to be zero.

[…]

3.1.7 Discussion

Overall, based on the available health information, the cost of bladder cancer due to arsenic in drinking water is estimated at $215.3M per year. The annual costs to implement a national POU intervention over 5 years of continued operation (i.e. annual average) in all households (assuming a US population of 325,310,000 and 2.58 persons per household) would range from $17.1B (reverse osmosis) to $23.6B (adsorptive media). Thus, under water quality conditions that meet the USEPA arsenic MCL, it would not be cost-effective to supply a point-of-use device in every household across the United States for arsenic removal alone.

In general, consumer perception that they are at risk of developing cancer (i.e., cancer risk probability is 1 in an individual life from arsenic exposure in water) drives the purchase of a POU device to avert disease. While the individual risk of cancer from arsenic is low, if an individual was certain to be the cancer case that would have been averted with a POU device, we can estimate the individual cost of a POU device relative to the aversion of a certain cancer case. See Table 16 for cost savings estimates for an individual at risk of developing cancer at 10 ppb arsenic concentration. While the assumption of a cancer probability of 1 is not plausible, targeting specific higher risk groups for POU intervention increases the individual cost benefit.

To better explain the cost-effectiveness of arsenic removal using a POU device, we aimed to highlight a community exposed to high levels of arsenic in drinking water. However, under our assumptions of a cancer probability of 1, the risk and cost-effectiveness remain largely unchanged despite higher levels of arsenic exposure. In order to improve upon the cost-effectiveness of POU devices to remove arsenic and reduce arsenic associated cancer (e.g. bladder) risks, rates of cancer at various concentrations in drinking water must be measured and incorporated into the developed calculator.

A device certified for arsenic reduction as per ANSI/NSF Standard 53 must demonstrate a minimum reduction of 80% for an influent concentration of 50 ppb or a minimum of 96.7% for an influent challenge level of 300 ppb. The range of cost and benefit values presented in Table 10 are similar to the ANSI/NSF Standard and thus encompass both optimal and real-world study results. If and when a family is concerned about the cancer risk associated with arsenic in drinking water and decides to buy and install a certified POU device, their own specific benefit derived from such an action will range from $36,388 to $60,443 (see Table 16).

Table 15. Cost-effectiveness for each POU device

POU Type	Lowest reported post filter concentration (µg/l)	Cost of unit (initial)	Cost of unit (annual maintenance)	5 year cost	Lifetime cost of unit (70 years)[A]	Risk of lifetime cancer at lowest reported post filter concentration	Delta risk from USEPA (10 µg/l = 5)	Cost per risk reduction [B]
No treatment	10.00	$0	$0	$0	$0	5.00	0.00	$0
Reverse Osmosis	0.03	$300	$95	$680	$9,520	0.60	4.40	$23,233
Adsorptive Media	0.69	$520	$104	$936	$7,644	0.30	4.70	$22,149
Distillation	3.00	$340	$100	$740	$10,360	1.50	3.50	$28,967

A. Lifetime unit cost assuming unit replaced every 5 years for 70 years

B. Assuming equal USD value for 70 years

Table 16. Cost savings given cancer probability of 1 and initial arsenic concentration of 10 µg/l

Point-of-Use device	% As reduction	Post filter concentration	Post intervention lifetime cancer risk (per 10,000)	Lifetime POU cost	Benefits
No treatment	0%	10.0	5.00	$0	$0
Reverse Osmosis	81.0	1.90	0.95	$9,520	$49,454
Adsorptive Media	59.7	4.03	2.02	$7,644	$36,388
Distillation	99.0	0.10	0.05	$10,360	$60,443

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