Cost-benefit analysis of point-of-use devices for health risks reduction from pathogens in drinking water

Marc Verhougstraete, Kelly A. Reynolds, Jennifer Pearce-Walker and Charles Gerba

ABSTRACT

Microbial contamination of drinking water post-municipal treatment is difficult to predict as a risk factor for human health. One method to reduce morbidity or mortality from unpredictable exposures is through point-of-use (POU) treatment devices. The goal of this project was to assess the cost-benefit of POU water treatment at the tap in terms of protection from microbes in drinking water. This project estimated: (1) incidence of acute illness (AI), sequela, and mortality associated with waterborne pathogens; (2) illness reduction rates from using POU devices; and (3) healthcare cost reductions associated with POU devices. Infection rates and costs associated with 10 of the most common waterborne pathogens were identified and used to calculate national annual costs. We estimated 9M AI, 0.6M sequela, and 1,400 mortality cases that occur annually in the USA from these pathogens. The greatest cost-benefit was seen when considering the totality of disease burden reduction (AI, sequela, and mortality) including all pathogens at a national level and applying a 35% infection reduction, resulting in a total cost per averted disease case of $1,815. This study suggests that it is cost-beneficial to prevent water-related illness using POU devices.

Key words | drinking water, point-of-use devices, waterborne diseases, waterborne pathogens

HIGHLIGHTS

- US experiences an estimated 9M cases of acute water-related illnesses each year.
- Point-of-use devices are cost-effective when all pathogens and disease reductions considered.
- POU devices could prevent 3.4M cases of acute, sequela, and mortality annually in the USA.

INTRODUCTION

Microorganisms in water typically cause respiratory illness (e.g., legionellosis) and intestinal illnesses (e.g., gastroenteritis) but can also cause more severe illnesses, including hepatitis, paralysis, meningitis, and neurological disorders. Waterborne organisms capable of causing disease may originate from fecal contamination of the water (waterborne) or from the growth of the organisms in the water (water-based). Waterborne pathogens are assumed to be present in surface waters in the United States. Many waterborne pathogens are zoonotic, infecting both animals and humans. Among these, the most important are Cryptosporidium, Giardia, microsporidia, Salmonella, Campylobacter, and Escherichia coli 0157:H7. Legionella and the Mycobacterium avium complex are the most common causes of water-based infections associated with drinking water. Water-based pathogens are capable of growth in distribution systems, and thus present a risk in treated water.

Microbial pathogens in drinking water are difficult to control for a number of reasons. Microorganisms are randomly distributed in water, making contamination more difficult to detect compared with chemical contaminants that dissolve homogeneously in water. Generally, the
levels of waterborne pathogens vary greatly over time in surface waters, which can become contaminated following rainfall runoff containing animal wastes and sewage overflows. The variability of microbial concentrations in untreated surface and groundwater makes it difficult to consistently remove all pathogens to desired levels during drinking water treatment. Although disinfection of wastewater largely eliminates the problem of enteric bacteria, disinfectant type and typical concentration levels may not effectively prevent the discharge of more resistant pathogens such as Cryptosporidium, Giardia, and enteric viruses into surface waters.

Contamination of unprotected drinking water wells or throughout the drinking water distribution system are significant routes of microbial exposure. Water treated to meet standards at the plant may be contaminated via intrusion events or regrowth in the distribution system or premise plumbing. Recontamination can occur from pipe breaks, leaky cross-connections, or back siphoning. Illicit connections and cracks in utility distribution systems occur, allowing the potential for contaminants to enter the distribution system. It has been shown that routine repair and maintenance of the distribution system can result in contamination of the drinking water (LeChevallier et al. 2003; Nygård et al. 2007). Additionally, the growth of organisms can occur in the distribution system, even in the presence of residual disinfectants (Pepper et al. 2004; Reynolds et al. 2008).

Another water safety concern is the use of privately owned, contaminated drinking water wells (Marrero-Ortiz et al. 2009). Fourteen percent of the US population, or 44.1 million persons, rely on private drinking water wells (Ayotte et al. 2017). These wells are usually unregulated and, therefore, are less likely to be routinely monitored or treated, potentially placing users at an increased risk of pathogen exposure. In fact, between 1971 and 2008, private wells were responsible for 30% of drinking water outbreaks reported to the Centers for Disease Control and Prevention (CDC) (Wallender et al. 2013). Typically, private wells are shallower than public wells and are more susceptible to contamination from surface waters (Marrero-Ortiz et al. 2009; Kumar et al. 2010). Groundwater sources for private wells may be contaminated by infiltration from rivers, septic tank leach fields, or leaking sewer lines. Cross-contamination with septic system waste due to poor design, maintenance, or improper spacing is listed as the primary cause. Contamination of groundwater is reportedly widespread (Curriero et al. 2001; Auld et al. 2004; Thomas et al. 2006; Fong et al. 2007; Tornevi et al. 2015) and numerous outbreaks of waterborne disease associated with groundwater are well documented (Lee et al. 2002; Fong et al. 2007; Reynolds et al. 2008). In the most recent waterborne outbreak report from the CDC, groundwater accounted for 33.3% (n = 14) of outbreaks and 157 outbreak-related cases of illness in the United States between 2013 and 2014 (Benedict et al. 2017). Drinking untreated groundwater was the second most common cause of outbreaks and the number one predominant source of illness cases.

Since the passage of the Safe Drinking Water Act in 1974, the United States Environmental Protection Agency (USEPA) has been responsible for developing standards limiting exposure to contaminated drinking water. There are two types of standards regulating contaminants: (1) primary standards that regulate substances harmful to human health and (2) secondary standards that address substances related to aesthetics. The Maximum Contaminant Level (MCL) is designed to protect human health and refers to the maximum concentration of a harmful substance allowed in the drinking water. Since even one organism ingested is capable of causing disease, any microorganism presence in water is considered unsafe and the USEPA set the Maximum Contaminant Level Goal (MCLG) for pathogens in water at zero. It is currently impossible to monitor for the more than 200 known waterborne pathogens so rather than defining an MCL, the USEPA treatment standards are set to achieve risk of infection no greater than 1:10,000 per year. Treatment standards are set based upon the estimated numbers of pathogens in the water to be treated. To achieve the USEPA goal of a risk of 1:10,000 per year of infection, the levels of some pathogens have to be less than one in 10,000–1,000,000 l of drinking water (Craun 1993). Risk estimates inherently include a level of uncertainty because they are often derived from animal studies and extrapolated to estimate the probability of adverse human health outcomes to very low levels of exposure via drinking water. To compensate for this uncertainty, safety factors are used extensively.

Point-of-use (POU) devices may provide the consumer with additional protection and lower the risk of adverse
health effects. POU technologies have been shown to reduce pathogen levels in drinking water and offer significant reductions in diarrheal disease rates (Souter et al. 2005; Sobsey et al. 2008). During the Milwaukee Cryptosporidium outbreak of 1993, the largest record in US history, persons who had a POU filtration device in place reported significantly lower incidences of diarrhea compared with those without a POU device (Addiss et al. 1996). A randomized intervention trial found highly credible gastrointestinal illness rates were higher in groups consuming tap water compared with those consuming water purified with reverse osmosis (RO) and children <12 years of age who consumed tap water without POU treatment experienced the highest gastrointestinal illness rates of the study (Payment et al. 1997). Recent studies have shown that filters placed on taps can reduce the number of illness associated with Pseudomonas aeruginosa infections from 3.9 ± 2.4 in unfiltered water to 0.8 ± 0.8 with filtration and eliminate mortality associated with these infections (Trautmann et al. 2006). The additional removal of contaminants beyond standard treatment lowers exposure risk and subsequent risk of adverse health outcomes. The additional protection allotted from POU devices is especially important for sensitive populations (e.g., newborns, children, pregnant women, immunocompromised individuals, and the elderly) where exposures to drinking water contaminants are more likely to result in adverse health outcomes including increased mortality.

Previous epidemiological intervention studies have demonstrated illness reduction due to POU water treatment. These reduction rates can be used to model the decrease in illness an individual is expected to experience over a given timeframe or to predict the number of acute infections, sequela, and mortality cases. Hellard et al. (2001) reported finding Campylobacter spp., pathogenic E. coli, Salmonella spp., adenovirus, rotavirus, Cryptosporidium spp., and Giardia spp. in the feces of study participants with highly credible gastroenteritis. In nearly all highly credible gastroenteritis fecal samples, the group consuming water treated with 1-μm absolute filter and an ultraviolet light had fewer pathogens in their feces compared with the group consuming unimproved tap water (Hellard et al. 2001). These pathogens, and others, have the ability to produce lasting illnesses beyond acute infections requiring hospitalization or mortality at varying rates.

The goal of this project was to provide an assessment of the cost-benefits of POU water treatment at the tap as a final barrier of protection from microbes in drinking water. This project estimated: (1) the incidence of acute illness (AI), sequela, and mortality in the USA associated with waterborne pathogens; (2) illness reduction rates stemming from the use of POU devices; and (3) healthcare cost reductions associated with POU devices. This information was then paired with recorded costs of healthcare resulting from waterborne disease and the implementation of POU systems to create a cost-benefit analysis and accompanying model to analyze the benefit of POU treatment versus the annual costs.

METHODS

Waterborne pathogens

Ten pathogens commonly identified as causative agents in drinking water-related illness were included in the cost-benefit analysis: Campylobacter spp., Salmonella spp., E. coli O157:H7, adenovirus, rotavirus, hepatitis A, Cryptosporidium spp., Giardia spp., norovirus, and Legionella. Many of these pathogens are included in the USEPA’s fourth Contaminant Candidate List (CCL) (US EPA 2017). Annual infection rates, incident cases, and health associated cost for each case of AI, sequela, and mortality for each pathogen were identified from the peer-reviewed literature. When only incident cases or infection rates were identified, the other value was calculated based on a US population of 330,172,512 (US Census Bureau, accessed 24 August 2020). Total annual AI, sequela, and mortality costs for each pathogen were calculated by multiplying the annual incident cases by cost for each case. When specific data were unavailable (e.g., infectious rates for adenovirus and hepatitis A and sequela rate for norovirus), an estimate was made based on relevant data identified in the literature.

Point-of-use/point-of-entry

POU/point-of-entry (POE) devices utilizing RO, activated carbon filtration, UV light treatment, and distillation and
certified by the American National Standards Institute (ANSI) and National Sanitation Foundation (NSF) to remove bacteria, viruses, and/or protozoa were included in the current study. POU specific costs for installation, operation, and maintenance were sourced from the publically available POU calculator (http://www.cyber-nook.com/chart/default.asp, accessed 15 June 2018). The initial startup, operational, and maintenance costs of each POU system were used to define an annual cost of use based on a 5-year device life expectancy. The 5-year cost of operating a POU device was calculated assuming a device installed on year one (cost\textsubscript{initial}) incurred annual operation and maintenance costs (cost\textsubscript{annual}) specific to each device and the device is replaced on a specific year (based on manufacturer recommendations) then the initial cost is incurred again. The average annual cost over a 5-year period was calculated by dividing the 5-year total cost by five. A modifiable 3% discount rate was used to calculate present day costs of POU devices in the online calculator. A summary of these costs and the ANSI/NSF certified POU/POE removal claims for each system are summarized in Table 1.

Cost effectiveness of RO systems

One review identified multiple studies which measured disease reduction with water treatment techniques; however, most of the studies were conducted in low- or middle-income countries using unimproved water sources or unimproved or unclear sanitation (Clasen et al. 2015), which do not represent the study location of the current study. The current study identified several household drinking water intervention studies to inform illness reduction rates using POU/POE (Table 2). One epidemiological study conducted in North America measured reductions in gastrointestinal illness rates associated with the use of a POU device (RO system with pre-filter and activated charcoal filtration) specifically for microbial control in drinking water (Payment et al. 1992b). Payment et al. reported an RO system with pre-filteration and activated carbon filtration resulted in a 35% reduction of gastrointestinal illness case incidence. They did not measure or indicate the causative agent of gastrointestinal illness or those removed from the drinking water, and therefore, illness reduction could have been a reduction in any waterborne pathogen. It has been demonstrated that

### Table 1 | POU/POE devices, associated costs, and ANSI and NSF certified POU/point-of-entry device removal claims

<table>
<thead>
<tr>
<th>POU/POE (ANSI/NSF Standard)</th>
<th>POU/POE reduction claim</th>
<th>Initial cost</th>
<th>Operation and maintenance cost (per year)</th>
<th>5-year total cost\textsuperscript{b}</th>
<th>Annual cost over 5 years\textsuperscript{c}</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activated carbon (53)</td>
<td>Bacteria, protozoa, lead</td>
<td>$32</td>
<td>$61\textsuperscript{e}</td>
<td>$336</td>
<td>$67</td>
<td>NSF International (2005), USEPA (2006)</td>
</tr>
<tr>
<td>UV treatment (55)</td>
<td>Bacteria, viruses, protozoa</td>
<td>$1,122</td>
<td>$117</td>
<td>$1,588</td>
<td>$318</td>
<td>NSF International (2005), USEPA (2006)</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Under NSF P231 or USEPA Purifier Guide Standard, POU devices claiming microorganism reductions are required to ‘remove, kill or inactivate all types of pathogenic organisms’ at the following rates: Bacteria: 6 Log, viruses: 4 Log, and protozoan cysts: 3 Log.

\textsuperscript{b}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 15 June 2018).

\textsuperscript{c}5-year cost divided by 5 years.

\textsuperscript{d}$65 per year after the first year for filter cartridge replacement and $35 every other year for membrane cartridge replacement.

\textsuperscript{e}Replace cartridge five times per year at $12.20 per filter.

\textsuperscript{f}$193 annual electrical cost including year 1.
## Table 2 | Household drinking water interventions demonstrating reduction in illness

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Montreal, Canada</td>
<td>Montreal, Canada</td>
<td>California, USA</td>
<td>Iowa, USA</td>
<td>California, USA</td>
<td>Wisconsin, USA</td>
<td>Wisconsin, USA</td>
<td>California, USA</td>
<td>Melbourne, Australia</td>
</tr>
<tr>
<td>Sample size (individuals)</td>
<td>2,408</td>
<td>5,253</td>
<td>236</td>
<td>1,296</td>
<td>988 only elderly</td>
<td>153 Children Ages 1–8</td>
<td>1,187 Households Ages 13–18</td>
<td>614 HIV Positive</td>
<td>2,811</td>
</tr>
<tr>
<td>Sham device</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>UV device operating at well head</td>
<td>No, boiled water</td>
<td>Yes</td>
</tr>
<tr>
<td>Treatment applied</td>
<td>Flocculation, filtration, ozonation, and chlorination</td>
<td>Flocculation, filtration, ozonation, and chlorination</td>
<td>Conventional treatment</td>
<td>Conventional treatment</td>
<td>Groundwater under the influence; chlorination</td>
<td>Untreated private wells</td>
<td>Public groundwater supplies</td>
<td>Municipal</td>
<td>Combination of filtration and UV</td>
</tr>
<tr>
<td>Finished water quality</td>
<td>Met standards</td>
<td>Met standards</td>
<td>Met standards</td>
<td>Met standards</td>
<td>Met Standards</td>
<td>Fecal streptococcus present in some wells</td>
<td>Met standards</td>
<td>Not stated</td>
<td>Not stated</td>
</tr>
<tr>
<td>Distribution system</td>
<td>Not reported</td>
<td>No reports of fecal contamination</td>
<td>Not reported</td>
<td>Met standards</td>
<td>Met Standards</td>
<td>Fecal streptococcus present in some wells</td>
<td>Met standards</td>
<td>Not stated</td>
<td>Total coliforms, HPC, Aeromonas spp., Campylobacter spp. Present in some samples</td>
</tr>
<tr>
<td>Cases of illness attributable to tap water (%)</td>
<td>35</td>
<td>12</td>
<td>24</td>
<td>Two study periods 0.008 (I) 0.08 (II)</td>
<td>12</td>
<td>11% of diarrhea in children</td>
<td>6 and 22%; as high as 63% in children &lt; when norovirus present</td>
<td>64</td>
<td>4</td>
</tr>
</tbody>
</table>
RO removes nearly all viruses, bacteria, and protozoa from seeded drinking water (Espinosa-García et al. 2014). Based on available and applicable data, we created a cost-benefit calculator based on RO systems with pre-filtration and activated carbon filtration assuming a 55% reduction in AI. No other POU types certified for microorganism removal from water were included in the cost-effectiveness analysis. The cost-benefit calculator assessed only gastroenteritis and did not consider other illnesses attributable to waterborne organisms or high-risk populations. These parameters were used to produce a percent reduction of gastroenteritis illness cases attributable to POU water treatment, which then informed the cost-benefit analysis. Annual estimates of disease were coupled with associated costs from each pathogen with the illness rate reduction expected from RO use, a cost-effectiveness value was defined. This information and an assumed reduction of case incidence equal to 35%, per Payment et al. (1991b), using an RO system with pre-filtration and activated carbon filtration were used to calculate post-treatment AI, sequelae, and mortality rates and incident cases for each of the pathogens.

A national intervention cost for RO systems was calculated by using the following equation:

\[
\text{USD National Interventation} = POU_{\text{annual}} \times \left( \frac{\text{Population}}{\text{Individuals house}} \times \%\text{Households}_{\text{No POU}} \times \%\text{Household Will use POU} \right) \quad (1)
\]

where \(POU_{\text{annual}}\) is the cost to run one RO system based on an initial cost of $318, $65 per year after the first year for filter cartridge replacement, and $35 every other year for membrane cartridge replacement for a total of $648 over 5 years. The 5-year total was divided by five to obtain \(POU_{\text{annual}}\). The national intervention cost calculation assumed that an RO system would be used in every household in the United States (330,172,512 population) and each household averaged 2.58 individuals (Lofquist et al. 2012). An estimated 32% of households currently use an under sink POU (e.g., RO) and were therefore excluded from the national household calculations (Water Quality Association 2019). The national morbidity and mortality case calculations following POU interventions incorporated a 75% usage rate for those households who would be expected to use a POU for all consumption purposes if it was installed in their home (Lykins et al. 1995), effectively reducing POU disease reduction rates by 25% at a national level. The 5-year timeframe was used following manufacturer estimates of unit life span. A national household-level approach was considered the most effective way to demonstrate POU treatment importance to prevent diseases as the odds of becoming infected with a pathogen from drinking water in the United States is low (Table 3), resulting in unrealistic cost-benefit calculations at the individual level.

A monetary value per averted case of acute, chronic, or mortal illness was calculated for each pathogen using Equation (2). This was accomplished by taking the absolute value of the cost difference (health costs of no POU (\(\text{cost}_i\)) minus the cost of using a POU device (\(\text{cost}_n\)) divided by the case difference (the number of cases after POU treatment (\(n_i\)) minus the number of cases without POU treatment (\(n_n\))).

\[
\text{USD per averted case} = \left| \frac{\text{Cost}_i - \text{Cost}_n}{\text{Cases}_i - \text{Cases}_n} \right| \quad (2)
\]

A modifiable calculator to determine the cost-benefit of implementing POU devices to reduce pathogen-associated morbidity and mortality cases was created using Excel (Microsoft Corporation) and is included in the Supplemental Material. The final result of the calculator is a USD value representing the annual averted cost per case if a nationwide household-level RO intervention was implemented. To calculate this final result, the difference in cost between a nationwide intervention and healthcare costs (healthcare costs for all pathogens and all types of cases: AI, sequelae, and mortality) was divided by the difference in the annual number of cases of AI, sequelae, and mortality across all pathogens with and without intervention implementation.

**RESULTS**

A summary of each pathogen of interest and their associated AI, sequelae, and mortality rates, incident cases, and associated medical costs for each category and pathogen are
<table>
<thead>
<tr>
<th>Pathogen</th>
<th>Infection rate</th>
<th>Incident cases</th>
<th>AI cost per case</th>
<th>Total AI cost</th>
<th>Sequela rate (%)</th>
<th>Sequela cases</th>
<th>Sequela cost per case</th>
<th>Total cost of sequela</th>
<th>Mortality rate (%)</th>
<th>Mortality cases</th>
<th>Total mortality cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campylobacter spp.</td>
<td>0.10</td>
<td>320,000</td>
<td>$190</td>
<td>$60,800,000</td>
<td>10.2</td>
<td>32,640</td>
<td>$15,711</td>
<td>$512,807,040</td>
<td>0.1</td>
<td>32.6</td>
<td>$282,576,132</td>
</tr>
<tr>
<td>Salmonella spp.</td>
<td>0.02</td>
<td>59,000</td>
<td>$190</td>
<td>$11,210,000</td>
<td>48.6</td>
<td>28,645</td>
<td>$15,711</td>
<td>$450,033,740</td>
<td>0.1</td>
<td>28.6</td>
<td>$247,985,663</td>
</tr>
<tr>
<td>E. coli O157:H7</td>
<td>0.05</td>
<td>150,000</td>
<td>$420</td>
<td>$63,000,000</td>
<td>29.5</td>
<td>44,250</td>
<td>$55,617</td>
<td>$2,461,052,250</td>
<td>0.2</td>
<td>88.5</td>
<td>$766,176,095</td>
</tr>
<tr>
<td>Adenovirus</td>
<td>0.82</td>
<td>2,700,073</td>
<td>$190</td>
<td>$513,013,870</td>
<td>0.78</td>
<td>21,061</td>
<td>$15,711</td>
<td>$330,882,606</td>
<td>0.002</td>
<td>0.4</td>
<td>$3,646,577</td>
</tr>
<tr>
<td>Rotavirus</td>
<td>1.06%</td>
<td>3,500,000</td>
<td>$62</td>
<td>$217,000,000</td>
<td>1.67</td>
<td>58,331</td>
<td>$2,487</td>
<td>$145,069,197</td>
<td>0.01</td>
<td>5.8</td>
<td>$50,499,229</td>
</tr>
<tr>
<td>Hepatitis A</td>
<td>0.01</td>
<td>32,531</td>
<td>$190</td>
<td>$6,180,890</td>
<td>13.0</td>
<td>429</td>
<td>$19,716</td>
<td>$83,739,555</td>
<td>0.5</td>
<td>127</td>
<td>$5,049,229</td>
</tr>
<tr>
<td>Cryptosporidium</td>
<td>0.51</td>
<td>1,691,612</td>
<td>$190</td>
<td>$321,406,280</td>
<td>15.0</td>
<td>253,742</td>
<td>$25,662</td>
<td>$6,004,038,472</td>
<td>0.5</td>
<td>127</td>
<td>$5,049,229</td>
</tr>
<tr>
<td>Gastrointestinal pathogen</td>
<td>0.08</td>
<td>260,000</td>
<td>$88</td>
<td>$22,880,000</td>
<td>67.0</td>
<td>174,200</td>
<td>$11,120</td>
<td>$203,514,400</td>
<td>0.0001</td>
<td>0.2</td>
<td>$1,092,812</td>
</tr>
</tbody>
</table>

References:
- Rotavirus: Gerba et al. (20139), Ho et al. (2013), Saulsbury et al. (2013).
- Cryptosporidium: Bennett et al. (20139), U.S. EPA (20131), Hunter et al. (20139), Saidenberg et al. (20139), Faust et al. (20139).
- Gastrointestinal pathogen: Bennett et al. (20139), Estimating the burden of disease associated with outbreaks of waterborne disease (2013), Hunter et al. (20139), Rocheleau et al. (20139), Faust et al. (20139), Schafferg et al. (20139), Cerna et al. (20139).
defined in Table 3. Figure 1 summarizes the cost and total number of cases associated with AI, sequela, and mortality for each pathogen. Based on the identified infection rates and US population, it is estimated that more than 9,000,000 AI cases occur each year attributable to the presence of the 10 included waterborne pathogens in drinking water. Assuming a US population of 330,172,512, the pathogens and infection rates would result in 9,026,216 cases of AI, 618,047 sequela cases, and 1,470 mortalities associated with drinking water annually. The most significant pathogens driving waterborne illness cases each year were rotavirus ($n_{total} = 3,558,337$ total AI, sequela, and mortality cases), adenovirus ($n_{total} = 2,721,134$), and Cryptosporidium spp. ($n_{total} = 1,946,623$). Cryptosporidium spp. had the highest frequency of sequela and mortality with an estimated 253,742 and 1,269 cases of each per year, respectively. Cryptosporidium spp. also had the highest costs associated with sequela and mortality with estimated national annual costs of $6.00B and $11.0B, respectively. Legionella infections from drinking water consumption (e.g., aspiration of drinking water) resulted in the lowest AI cases compared with other pathogens.

The POU water treatments identified for the purposes of this study included RO, activated carbon, UV treatment, adsorptive media, pour-through granular activated carbon pitcher filter, distillation, and ion exchange (softener). Costs and the ANSI/NSF certified POU/POE device removal claims for each of these systems are summarized in Table 1. Over a 5-year period, RO ($680), activated carbon ($546), and pour-through filtration units ($645) have similar costs. 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. However, RO was the only POU certified for microorganism removal included in the cost-benefit analysis due to the availability of applicable health reduction data.

Applying a 35% reduction in drinking water associated illness using a RO system (Payment et al. 1994a) to initial morbidity and mortality rates, an estimated 3,159,176 of AI cases, 216,316 sequela cases, and 515 mortalities would be expected annually for a total of 3,376,007 total cases. The reductions of AI, sequela, and mortality cases for each pathogen are summarized in Figure 2. The rates of illness

<table>
<thead>
<tr>
<th>Pathogen</th>
<th>Infection rate</th>
<th>Incident cases</th>
<th>AI cost per case</th>
<th>Total cost AI</th>
<th>Sequela rate (%)</th>
<th>Sequela cases</th>
<th>Sequela cost per case</th>
<th>Total cost of sequela</th>
<th>Mortality rates (%)</th>
<th>Mortality cases</th>
<th>Total mortality cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norovirus</td>
<td>0.09</td>
<td>300,000</td>
<td>$136</td>
<td>$40,800,000</td>
<td>0.001</td>
<td>300</td>
<td>$190</td>
<td>$2,470,000</td>
<td>0.001</td>
<td>650</td>
<td>$135,000</td>
</tr>
<tr>
<td>L. pneumophila</td>
<td>0.004</td>
<td>13,000</td>
<td>$196</td>
<td>$2,552,000</td>
<td>0.001</td>
<td>500</td>
<td>$140</td>
<td>$70,000</td>
<td>0.001</td>
<td>0.001</td>
<td>$1,269</td>
</tr>
</tbody>
</table>

*Based on a single life value of $8,657,357.

**No specific data available—values estimated from the relevant literature.

Table 1 continued
associated with the drinking water varied widely (67% for *Giardia* sequela to 0.0001% for norovirus mortality) between individual pathogens and reflected source of water, type of treatment, and types of pathogens present in the raw water source (Table 3).

At the national level, an estimated 87,022,212 households would require installation of an RO system and outfitting all of these households would cost a total of $11.3B/year. The total cost of disease burden for all pathogens and health outcomes (i.e., AI, sequela, and mortality) would be $24.2B. Results from the cost-effectiveness analysis demonstrate that the highest cost-effectiveness is seen when the totality of disease burden (AI, sequela, and mortality) from all pathogens is considered. When all the pathogens and disease burden (acute, sequela, and mortality cases) are considered, the cost per averted disease case was $1,815 annually. The lowest return on investment (i.e., the highest cost spent considering the cost of disease, Equation (2)) for chronic sequela and mortality at a national level was associated with norovirus because there are very few cases but intervention costs remain the same as for other organisms with a higher case rate. The cost averted when using an approved POU treatment is summarized in Table 4, and results are presented per individual pathogen and overall.

**DISCUSSION**

This study aimed to estimate the AI, sequela, and mortality rates associated with waterborne pathogens in drinking water. A single infection from a waterborne pathogen costs between $62 (acute infection) and $8.7M (death) resulting in a total burden of drinking water-related
morbidity and mortality cases \( (n = 9,645,734 \text{ includes AI, sequela, and death}) \) in the United States of $24.2B annually. POU devices are cost-effective for reducing exposures to microorganisms on a short-term scale and cost between $67 and $318 to operate per year. Given the cost of morbidity/mortality and intervention at a single household level for a single pathogen of concern, a cost saving to an individual was not apparent. However, when considering that multiple people per household may benefit from a single device, water may contain more than one pathogen,
that each episode of AI could cost a family of three up to $1,260 ($420 per E. coli O157:H7 infection · 3 people = $1,260), and individuals could become infected more than once per year, a POU device would be cost-effective.

POU devices have been shown to be effective at controlling pathogen occurrences in drinking water. For the current project, an RO system with pre-filtration and activated carbon filtration was found to cost $130 annually over 5 years of operation. Assuming 2.58 people per household in the United States and 32% of households already have a similar device, a national campaign to outfit every household with an RO device for 1 year would cost $11.3B. The assumption is made that the RO treatment will reduce disease caused by any microorganism by 35%. The national intervention approach of the current study suggests that 6.6M fewer cases of AI could be achieved using RO. At the most basic level (e.g., cost of AI cases at a national level without RO and cost of AI cases at a national level with RO), this represents a reduction in healthcare costs of $928M. At the national level and when the burden of multiple waterborne pathogens was considered, the cost-benefits of POU devices become apparent for multi-occupant households.

The authors of this report recognize the wide range of costs associated with POU devices, healthcare costs, and infection rates. Calculations in the current project utilized values presented on the cyber-nook website (http://www.cyber-nook.com/chart/default.asp). These are plausible values which allow for individual calculations based on specific product costs or individual needs. The national intervention costs assumed every household would receive a POU device if they did not already have one installed, and did not consider the party responsible for paying for the device. However, it is known that only 67% of individuals would be willing to purchase a POU/POE device to remove microorganisms and only 75% of household will use their POU device for all consumption purposes (Lykins et al. 1995; Water Quality Association 2019). Future POU cost-effectiveness studies, including those performed by municipalities exploring POU deployment to customers, should factor these rates into estimated costs. While this study developed a deterministic model intended for maximum flexibility for specific information representative of a scenario or personal need in order to determine if a POU device is the correct option, future studies should incorporate probabilistic models to account for variability and uncertainty of POU costs.

Due to the complexity of the many health outcomes associated with the varying contaminants examined in this report, the multiple devices required to treat all drinking water contaminants, and the multitude of associated adverse health effects, it is difficult to produce a cost-benefit analysis

<table>
<thead>
<tr>
<th>Pathogen</th>
<th>C-E AI (USD/averted case)</th>
<th>C-E Sequela (USD/averted case)</th>
<th>C-E Mortality (USD/averted case)</th>
<th>Total disease burden (USD/averted case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campylobacter spp.</td>
<td>$47,523</td>
<td>$447,132</td>
<td>$456,696,083</td>
<td>$1,815</td>
</tr>
<tr>
<td>Salmonella spp.</td>
<td>$258,890</td>
<td>$512,472</td>
<td>$522,036,080</td>
<td></td>
</tr>
<tr>
<td>E. coli O157:H7</td>
<td>$101,362</td>
<td>$270,117</td>
<td>$161,026,343</td>
<td></td>
</tr>
<tr>
<td>Adenovirus</td>
<td>$5,405</td>
<td>$704,685</td>
<td>$36,287,645,958</td>
<td></td>
</tr>
<tr>
<td>Rotavirus</td>
<td>$4,284</td>
<td>$258,748</td>
<td>$2,609,459,927</td>
<td></td>
</tr>
<tr>
<td>Hepatitis A</td>
<td>$469,747</td>
<td>$3,588,685</td>
<td>$1,193,400,784</td>
<td></td>
</tr>
<tr>
<td>Cryptosporidium spp.</td>
<td>$8,781</td>
<td>$28,173</td>
<td>$312,607</td>
<td></td>
</tr>
<tr>
<td>Giardia spp.</td>
<td>$58,687</td>
<td>$86,252</td>
<td>$87,759,295,843</td>
<td></td>
</tr>
<tr>
<td>Norovirus</td>
<td>$50,781</td>
<td>$50,932,541</td>
<td>$50,965,702,371,063</td>
<td></td>
</tr>
<tr>
<td>Legionella</td>
<td>$1,175,874</td>
<td>$23,496,392</td>
<td>$458,713,956</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>$218,133</td>
<td>$8,032,520</td>
<td>$5,109,515,095,865</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>$4,284</td>
<td>$28,173</td>
<td>$312,607</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>$1,175,874</td>
<td>$50,932,541</td>
<td>$50,965,702,371,063</td>
<td></td>
</tr>
</tbody>
</table>
which wholly encompasses uncertainty and variability. The magnitude of the cost to prevent mortality, for example, is driven in part by the low risk of death from many of the included waterborne pathogens, making it not cost-effective for every individual to purchase a POU device with the intent to prevent death. The commonality of waterborne disease, however, makes it cost-effective to prevent such illness with the relatively low-cost purchase of a POU device. In addition, we understand there exists a compounding cost-benefit associated with the removal of multiple contaminants in drinking water that was not addressed in this manuscript. For example, the benefits of a device to remove a chemical, such as arsenic, and pathogenic microbes have a dual cost-benefit for both contaminants because there is always a benefit in illness reduction from microbes on an immediate timescale and a lifetime benefit for reducing chemical exposures.

Risk is nonlinear throughout an individual’s life. Therefore, the cost-benefit from operating a POU device would be even greater for a household with young people, immunocompromised, or elderly residents. This study assumed all US individuals and households would experience the same rate of AI, sequela, and mortality regardless of age, race, or preexisting conditions. This approach likely overestimates the burden in some populations and underestimates the burden for other populations (e.g., immunocompromised or elderly). However, making assumptions for such responses when insufficient data characterizing the infection rates for each waterborne pathogen on susceptible populations does not exist would only add to the uncertainty of the approach, diminishing the findings. While these unique circumstances were not included in the current cost-effectiveness assessment, they are important and should be considered in future projects that specifically aim to investigate the effects of POU devices to reduce risks in specific areas or subpopulations. Future work should include cost-benefit analysis for specific communities targeting high-risk populations or contamination probabilities. Public surveys of cost willing to pay to prevent disease from drinking water in these populations could further drive a more accurate cost-benefit analysis. Future research should also aim to define a dose–response relationship for waterborne pathogens and adverse health outcomes in vulnerable populations as well as the disease reductions using POU devices in the same populations. The calculators produced in the current study can be modified to better evaluate effects in the most at-risk individuals and communities.

Ingestion of a single organism can cause infection, and therefore, it is important that every precaution be taken to remove all pathogenic microorganisms from drinking water. Acute and chronic contamination of drinking water can occur without the knowledge of the consumer. Contamination of water with microorganisms can stem from many sources and even after water undergoes central municipal treatment, recontamination can occur throughout the distribution system. The USEPA reviews potential regulation of additional chemical and microbial contaminants in drinking water as new information becomes available on a 5-year cycle and many of the current study’s included pathogens are included in the final contaminant candidate list (CCL 4) (US EPA 2017). Current technologies used to treat water at the tap are capable of removing many of the emerging contaminants not currently regulated as well as those entering the system post-treatment. Assessing the potential health effects of microbial contamination is a continuing effort by regulatory agencies as new data become available. The current study supports the implementation of POU water treatment as a useful protective tool against uncertain microbial hazards or unforeseen contamination events.

ACKNOWLEDGEMENT

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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