Preventive Medicine Reports 38 (2024) 102588

Contents lists available at ScienceDirect

Preventive Medicine Reports

journal homepage: www.elsevier.com/locate/pmedr

An economic evaluation of strategies to ensure safer drinking water in the homes of families with young children in select United States locations

A.L. Cradock [a,*], J.L. Barrett [a], E. Nink [b], C. Wilking [c]

[a] *Prevention Research Center on Nutrition and Physical Activity, Department of Social and Behavioral Sciences, Harvard T.H. Chan School of Public Health, 677 Huntington Avenue, 7th Floor, Boston, MA 02115, United States*
[b] *ICF International, 1902 Reston Metro Plaza, Reston, VA 20190, United States*
[c] *Independent Legal Consultant, PO BOX 503, Cummaquid, MA 02637, United States*

ARTICLE INFO

Keywords:
Infant
Arsenic
Nitrate
Lead
Contamination
Cost analysis
Water supply
Water treatment
Drinking water

ABSTRACT

Introduction: In the United States, safe, accessible drinking water is not equitable due to source water contamination, unreliable water treatment, or hazardous plumbing infrastructure. Drinking water free of lead, nitrates, and arsenic is vital for infant and young children's health.
Methods: Researchers conducted a study combining single-case study review methods and economic evaluation for 6 US policies or programs. Researchers used case-study findings, activity-based costing, publicly available US population data, and existing literature to create 5-year cost projections (2020–2024) for strategies to address lead, nitrates, or arsenic in drinking water from private wells or community water systems for families with low incomes and young children aged 0–5y. Researchers estimated the number of households reached and the costs by activity and payer of implementing each policy or program using case-specific geographic location and eligibility criteria.
Results: The total number of households reached varied from 295 to 135,000 depending on water source, population of focus, and geographic location. Focused strategies reached higher proportions of families with low incomes and young children. Community water system and state-wide strategies had the broadest reach. The total annual program cost per household that received information about their water quality ranged from $75 to $2,780. Of this cost, the portion paid by the household varied from $0.12 to $1,590, not including mitigation.
Conclusions: These findings can inform local decisions about policies and programs in communities seeking to increase awareness and access to safer drinking water, particularly in homes of families with low incomes and young children.

1. Introduction

Water is ideal for children because it hydrates the body, is very low-cost, is calorie-free, and when consumed in place of sugary drinks, helps children maintain a healthy weight (Muckelbauer et al., 2016). Increased plain water intake supports oral health and prevention of inadequate hydration, which can affect cognition (Popkin et al., 2010). Water systems and environments are essential determinants of whether households or individuals have access to safe drinking water (Patel et al., 2020). Increasing safe drinking water access could impact beverage consumption preferences and patterns. Contaminants in drinking water, such as lead, arsenic, and nitrates, are especially harmful to infants, younger children, and pregnant people (Centers for Disease Control and Prevention, 2010; Rogan and Brady, 2009; Sherris et al., 2021). Safe home drinking water is vital for infant health, whether babies are formula- or breast-fed. Lactating people need access to safe drinking water while breastfeeding (US Department of Agriculture, 2019). Access to safe drinking water is also necessary for mixing formula to protect infants from contaminants, particularly given the formula intake volume relative to the infant's body size (US Environmental Protection Agency, 2012).

A lack of knowledge about home drinking water quality may result in exposure to contaminants in drinking water or poor perception and uncertainty about its safety. Safe, accessible drinking water is not universal due to problems such as source water contamination, unreliable water treatment, or potentially hazardous plumbing infrastructure

* Corresponding author.
E-mail address: acradock@hsph.harvard.edu (A.L. Cradock).

https://doi.org/10.1016/j.pmedr.2024.102588
Received 11 September 2023; Received in revised form 29 December 2023; Accepted 2 January 2024
Available online 3 January 2024

components (Edwards et al., 2009; Levin et al., 2023; Rogan and Brady, 2009). In 2019, 7 percent of children (0–17 years) in the United States were served by a community water system that did not meet all the health-based drinking water standards regulated by the federal government under the Safe Drinking Water Act (US Environmental Protection Agency). Exposure to unsafe drinking water is experienced disproportionately by families with low incomes (Allaire et al., 2018). The lack of access to quality drinking water may stem from unreliable source water, community water supplies, or home-based water system issues (McDonald and Jones, 2018). An estimated 37 million people get drinking water from private wells that are not subject to federal monitoring or regulation for any health-related standards (Johnson et al., 2019). Disparate impacts of water contaminants in under-resourced communities are shaped by a combination of the natural, built, and social-political environments and actors at the state, county, community, and household levels (Balazs and Ray, 2014). However, an equity framework (Kumanyika, 2019) adapted for this study illustrates actionable policy and systems changes to increase access and reduce deterrents to healthier drinking water sources, as well as supports for individual and community resources that improve social and economic capacity and build upon community assets (Wilking et al., 2022) to promote water security.

Water testing and remediation strategies such as bottled water, bulk water, or water filters can be effective short-term solutions for unsafe home drinking water, but these require financial resources (Rogan and Brady, 2009). Studies outside the US have delivered bottled water to homes to increase young children's water intake (Anand et al., 2007; Lahlou et al., 2015) and conducted education to change caregiver beverage serving strategies (Anand et al., 2007; Lahlou et al., 2015; McGowan et al., 2013). One study estimated the installation and maintenance costs for specific strategies (e.g., flushing, bottled water purchasing, filtration) to avoid lead in drinking water (Pieper et al., 2019). While informative, prior studies did not consider the implications of differential access to safe drinking water sources, costs of programmatic implementation, or sustainable policy or programmatic mechanisms for a US context for families with low incomes and young children.

This study aims to identify illustrative cases that leveraged policy and systems change through existing policies and programs in communities to mitigate contaminants including lead, nitrates and arsenic to increase access to safe home drinking water from public or private sources. It documents the activities, resources, and costs, by payer, associated with efforts to promote equitable access to safe home drinking water focused on families with low incomes and young children (i.e., children 0–5 years).

2. Methods

This simultaneous, complementary mixed-methods (Dopp et al., 2019) study combined traditional legal and policy research, single-case study review methods, and economic evaluation using activity-based-costing and resource allocation from a societal perspective to create 5-year cost projections that compare strategies that can increase access to safe drinking water in homes of families with young children (i.e., aged 0–5 years). The economic evaluation is presented here. Additional research findings are available elsewhere. The Office of Human Research Administration at the Harvard TH Chan School of Public Health reviewed and approved this study's protocol.

2.1. Selection of cases

Criteria for case study inclusion were that 1) the program or policy addressed home drinking water access or quality using 2) an approach that could be relevant for low-income families with young children (that were the study's focus population), 3) addressing lead, arsenic, or nitrate, three contaminants particularly harmful to children that could be mitigated with available approaches known to be effective, with 4) sufficient information available to describe activities and resources to enable costing, 5) focused on varied water sources, and 6) that authors deemed could be transferrable to other locations. The research team solicited suggestions from project advisors and key informants and conducted background research and literature reviews. From eight potential case studies identified through these activities, the research team selected six that represented a variety of features, including water source, implementation strategies, policy approaches, and drinking water contaminants that could meet inclusion criteria and were not duplicative. Researchers developed profiles for each case using available media reports, policy materials, and scholarly research and then identified one initial informant for each case study.

2.2. Key informant interviews

Recruitment and interview protocols were developed in 2020. A standard semi-structured interview protocol was developed with questions addressing the impetus for program/policy intervention, the timeline for completion of the intervention, implementation for the population of interest (low-income families with young children), and other activities, costs, and resources that would be required to implement the program, along with other information used to inform individual case studies (Wilking et al., 2022). The template was tailored to background research on each case.

Interviews with key informants took place via a call using Zoom software (Zoom Video Communications, Inc., San Jose, CA) from October 2020–January 2021, with one researcher conducting each interview. Interviews were audio-recorded, and the audio was transcribed using Zoom's software. Key informants included water utility staff, state agency staff, a representative of a private company that contracts on safe water projects, researchers, and community organization staff. The research team interviewed 16 key informants (100 percent of those invited) using snowball sampling from a primary informant. One researcher reviewed and cleaned transcripts of the recordings and extracted key findings. Key findings were reviewed by another researcher who returned to the transcripts if necessary. Researchers followed up with interview participants via phone/email in April–November 2021 after reviewing transcripts and compiling preliminary information and provided preliminary case summaries to key informants to ensure factual accuracy.

2.3. Economic evaluation

Researchers estimated the projected 5-year population reach and costs of implementing each policy or program in the geographic area according to the eligibility criteria of the specific case studied. Projections over 5 years were based on case estimates of program and policy reach, adoption, and reported cost for the duration the policy or program was in operation, with assumptions about hypothetical reach and cost if implemented for 5 years.

2.4. Estimated population reach

To identify the numbers of low-income families with young children reached, researchers used nationally representative data from the US American Housing Survey, existing local and national data on demographics and participation in state or federal programs (e.g., SNAP, WIC) of relevance to the case, and documentation gathered during case-study protocols (Appendix A).

2.5. Costing methods

The costing method, a single case-study economic evaluation, estimates the incremental cost of all activities associated with *each safe home drinking water policy or programmatic intervention* as compared to not implementing the strategy, using three steps: 1) Identification of the types of resources used for each intervention activity and the payer (e.g., state government, households, community water system); 2) Measurement of the quantity of each resource used and 3) Valuation of resource utilization in monetary terms. Researchers documented implementation activities for each case using key informant interviews with representatives and staff involved. Additionally, program-specific documents such as funding proposals, utility reports, and regulatory/approval documents were also reviewed as available. Researchers collected resource use, quantity, and value for each activity using a micro-costing framework (Sanders et al., 2016). This framework estimates costs for activities associated with programmatic outcome data on the population reached. Researchers collected data on the consumer price for needed materials and equipment (e.g., filtration systems, bottled water) and followed guidelines from the US Panel on Cost-Effectiveness in Health and Medicine to estimate one-year and ongoing recurring costs (Sanders et al., 2016). Researchers assessed costs from a societal perspective and reported costs by payer and activity (Sanders et al., 2016). Researchers projected water treatment costs incurred by households when not covered by the policy or program based on expected adoption. All costs are reported in 2020 dollars, with future costs discounted at 3 percent annually. Cost inputs were adjusted using the Consumer Price Index. Additional details on assumptions and data sources are found in Appendix A.

2.6. Outcomes

Researchers quantified the total numbers of households and eligible households with low income and young children, the numbers that would get information about their water quality, the proportion needing mitigation, and estimated the number of households that would adopt proven mitigation strategies, when needed, over 5 years using data derived from specific case research or from existing literature (Appendix A). Researchers estimated the 5-year total and average annual cost per household that gets information on water quality and per household adopting mitigation treatment. Researchers valued those incremental resources used to implement the policy or program in monetary terms by payer (e.g., state government, households, community water system) and implementation activity. Cost analysis outcomes present the total and average annual ongoing cost of implementation of intervention strategies over 5 years using assumptions based on uptake and population reach estimates from key informant interviews (e.g., number of families offered point-of-use filter systems in the community pilot intervention) or researcher derived estimates (e.g., number of households with young children that are participating in WIC programs).

3. Results

3.1. Case summary

Six case studies were completed, including three local and three statewide strategies (Table 1). The Northeast, Midwest, and West were represented, but the South was not. Two case studies were interventions within public water systems, and four were for private well owners. Two were initiated by policy changes, while others were programmatic efforts. Contaminants considered included nitrates, arsenic, and lead. Two strategies were conducted in conjunction with the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC). This program serves pregnant people and young children in families that meet certain (low) income thresholds and are deemed to be at nutritional risk. The cities of Cincinnati and Denver initiated programs as part of their public water supply systems' actions to replace the service lines made of lead that provide drinking water to homes, including both publicly owned service lines and service lines within a homeowner's property (i.e., "private-side"). Further details for each of these cases are available elsewhere (Wilking et al., 2022).

3.1.1. New Jersey Private Well Testing Act

State policy requiring home well water quality testing when a property is sold and every five years for rental properties served by wells. Households could adopt point-of-use systems or purchase bottled water when contaminants were present.

3.1.2. Well Testing Via Healthcare Clinics in New Hampshire and Vermont

Local program that educated primary care clinical providers to conduct screenings, offer home well water testing for arsenic at no charge to families with infants and conduct follow-up reminders. Households could adopt point-of-use/point-of-entry systems or purchase bottled water when contaminants were present.

Table 1
Descriptive features of six strategies to ensure safer drinking water in the homes of US families with young children 0–5y, 2020–2024.

Strategy	Case Study[a]	Population Focus[b]	Policy or Program	Water System Type	Water Testing and Treatment Provided or Required by Program or Policy				
					Private well testing	POU/POE Devices	Bottled Water Delivery	Lead Service Line Removal	Pitcher Filters
Rural Well Water Testing for Nitrate and Treatment Program	Porterville, California Program	Focused	Local Program	Private Wells	X	X	X		
Statewide Well Water Testing Requirement	New Jersey Private Well Testing Act	General	Statewide Policy	Private Wells	X				
Well Water Testing for Pregnant People Via WIC	New Hampshire's Water Well-Ness Initiative	Focused	Statewide Program	Private Wells	X				X
Well Water Testing for Families with Infants Via Healthcare Clinics	Well Testing Via Healthcare Clinics in New Hampshire and Vermont	General	Local Program	Private Wells	X				
Lead Service Line Replacement Program	Cincinnati's Enhanced Lead Program	General	Local Policy	Public Water System				X	X
Filter Pitcher Distribution to Households with Lead Service Lines	Denver Water's Filter Program	General	Local Program	Public Water System					X

POU: Point-of-Use, POE: Point-of-Entry.
[a] Further details on the background and activities of each case are available (Wilking et al., 2022).
[b] Focused populations included strategies that were conducted within populations of households with low incomes and children 0-5y.

3.1.3. New Hampshire's Water Well-Ness Initiative

Statewide initiative that trained WIC clinicians to conduct screenings of pregnant people, offer home well water testing, and, if needed, provide filter pitchers and filter cartridges free of charge.

3.1.4. Porterville, California Program

Local program that provided water sampling and testing services for nitrate along with associated education, water filtration systems (point of use), and bottled water delivery to WIC-eligible families free of charge via community organizations and a local WIC office.

3.1.5. Cincinnati's Enhanced Lead Program

Local ordinances prohibiting private lead service lines and providing local financing and subsidies for private lead service line replacements in collaboration with the public water system.

3.1.6. Denver Water's Filter Program

Local public water system program providing filter pitchers and replacement filter cartridges appropriate for household water needs free of charge to all properties with a known or suspected lead service line.

3.2. Economic evaluation results

The upper panel of Table 2 outlines the population within each geographic area that would meet the program or policy eligibility criteria and the people that obtained information about their household water quality, the number of those with low incomes and young children, and the proportion of these households estimated to need to implement a treatment strategy to address a contaminant. The proportion of households that obtained information about water quality that had low incomes and young children varied by case, from 100 percent in Porterville and New Hampshire's focused strategies, to between 4 and 26 percent in other broad population strategies. In the two strategies operating within the public water supply systems with lead service lines, the proportions of households needing mitigation treatments were higher than in other strategies (and individual household water quality testing was not a precursor to mitigation efforts). In other strategies, the levels of contaminants that require mitigation were expected to impact between 11 and 42 percent of households. This table also depicts the households whose water quality testing indicated a need for mitigation that were expected to adopt and use proven mitigation strategies based on existing program uptake data. Mitigation treatments included using bottled water, point-of-use or point-of-entry filtration devices, lead service line replacement, or a filter pitcher. Adoption was estimated to range from 62 to 80 percent of households. Detailed results and assumptions related to the population projections are found in Appendix A.

Table 3 depicts the average annual implementation costs (and percent of total average annual cost) by the categories of activities including program management, training, screening and outreach, sampling of water, and the treatment or mitigation costs that were part of each strategy. The proportional water treatment or mitigation costs varied from 24 to 100 percent of the average annual cost. In the cases of Cincinnati and Denver, costs estimated from program documents suggested bundled costs for certain activities that could not be further disaggregated. Detailed results and assumptions related to cost projections are available in Appendix A.

Table 4 depicts the total projected implementation costs over 5 years,

Table 2
Projected numbers of households reached over five years by six strategies to ensure safer drinking water in the homes of US families with young children 0-5y, 2020–2024.[a]

	Rural Well Water Testing for Nitrate and Treatment Program	Statewide Well Water Testing Requirement	Well Water Testing for Pregnant People Via WIC	Well Water Testing for Families with Infants Via Healthcare Clinics	Lead Service Line Replacement Program	Filter Pitcher Distribution to Households with Lead Service Lines
Water Source (Contaminant)	Private Well (Nitrate)	Private Well (Arsenic)	Private Well (Arsenic)	Private Well (Arsenic)	Public Water Supply (Lead)	Public Water Supply (Lead)
Geographic Area	Porterville, CA	New Jersey	New Hampshire	New Hampshire and Vermont	Cincinnati, OH	Denver, CO
Population meeting program/policy eligibility criteria						
Total	1,150	51,900	4,370	14,200	39,900	153,000
With Low Income & Young Children[b]	1,150	2,190	4,370	3,720	3,720	7,750
Population that gets information on their household water quality						
Total	295	51,900	1,970	2,170	6,510	135,000
With Low Income & Young Children[b]	295	2,190	1,970	565	608	6,490
Total in the First Year	59	10,400	394	433	1,180	106,000
Percentage (%) needing treatment due to contaminant exceedance	42.4	11.2	30	14.3	100 (with lead service lines)	100 (of enrolled)
Population adopting water treatment strategy						
Percentage (%) adopting treatment among those needing treatment	72.0	70	70	70	62.2	80
Total	90	4,070	414	217	4,050	108,000
With Low Income & Young Children[b]	90	172	414	57	378	5,190
Total in the First Year	18	814	83	43	736	84,700
Treatment Type[c]	Bottled water or POU device	Bottled water or POU/POE device	Filter pitchers	Bottled water or POU/POE device	LSLR with one-time filter pitcher	Filter pitchers (until LSLR and for 6 months thereafter)

POU: Point-of-Use, POE: Point-of-Entry, LSLR: Lead Service Line Replacement.
[a] Additional details on assumptions, data sources, and projected outcomes are found in Appendix A1.1, A2.1, A3.1, A4.1 A5.1, A6.1.
[b] Households with low income and young children are defined as households with children under 6 years of age and income less than 185 percent of the federal poverty level.
[c] Treatment Type includes treatment provided by programs as well as assumed treatment that households would adopt or maintain as a result of the program or policy.

Table 3
Projected average annual cost by activity category over five years of six strategies to ensure safer drinking water in the homes of US families with young children 0-5y, 2020–2024.[a]

	Rural Well Water Testing for Nitrate and Treatment Program	Statewide Well Water Testing Requirement	Well Water Testing for Pregnant People Via WIC	Well Water Testing for Families with Infants Via Healthcare Clinics	Lead Service Line Replacement Program	Filter Pitcher Distribution to Households with Lead Service Lines
Geographic Area	Porterville, CA	New Jersey	New Hampshire	New Hampshire and Vermont	Cincinnati, OH	Denver, CO
Average Annual Implementation Cost by Activity	*$ (% of Total)*	*$ (% of Total)*	*$ (% of Total)*	*$ (% of Total)*	*$ (% of Total)*	*$ (% of Total)*
Project Management/ Oversight	$51,700 (70)	$2,790,000 (14)	$29,600 (27)	N/A	N/A (See Water Treatment[b])	$3,140,000 (40)[c]
Training	$291 (<1)	N/A	N/A	$3,400 (1)	N/A	N/A
Screening, Outreach, and/or Education	$394 (1)	N/A	$10,500 (10)	$3,020 (1)	N/A (See Water Treatment[b])	N/A (See Project Management/ Oversight[c])
Water Sampling	$3,680 (5)	$11,700,000 (61)	$28,400 (26)	$118,000 (31)	N/A	N/A
Water Treatment[d]	$17,500 (24)[e]	$4,810,000 (25)[f]	$39,800 (37)[g]	$256,000 (67)[f]	$3,290,000 (100)[b]	$4,800,000 (60)[h]
Total Average Annual Implementation Cost	$73,600 (100)	$19,300,000 (100)	$108,000 (100)	$380,000 (100)	$3,290,000 (100)	$7,940,000 (100)

[a] Additional details on assumptions, data sources, and costs by activity and payer are in Appendix A1.2, A2.2, A3.2, A4.2 A5.2, A6.2.
[b] Water Treatment cost is based on a reported unit cost for lead service line replacement that includes the costs of communication, outreach, coordination efforts, and replacement of the line and providing post-replacement filters.
[c] Project Management/Oversight cost includes the costs of communication and outreach efforts.
[d] Treatment Type includes treatment provided by programs as well as assumed treatment that households would adopt or maintain as a result of the program or policy.
[e] Includes the cost of point-of-use filtration system materials, installation, and one year of maintenance or the cost to provide bulk water deliveries per household, as well as participant time and material costs to maintain point-of-use filtration systems after the first year.
[f] Includes the initial and ongoing costs of using bottled water or treating water with a reverse osmosis point-of-entry or point-of-use device.
[g] Includes equipment and shipping costs of pitchers and replacement filters per household, as well as participant time costs to discuss drinking water test results and filter use with a program contractor on the phone and to complete program surveys required for program participation.
[h] Includes procurement, equipment, and shipping costs of pitchers and replacement filters per household.

Table 4
Projected implementation costs over five years of six strategies to ensure safer drinking water in the homes of US families with young children 0-5y, 2020–2024.[a]

	Rural Well Water Testing for Nitrate and Treatment Program	Statewide Well Water Testing Requirement	Well Water Testing for Pregnant People Via WIC	Well Water Testing for Families with Infants Via Healthcare Clinics	Lead Service Line Replacement Program	Filter Pitcher Distribution to Households with Lead Service Lines
Geographic Area	Porterville, CA	New Jersey	New Hampshire	New Hampshire and Vermont	Cincinnati, OH	Denver, CO
Total Implementation Cost over 5 Years	$368,000	$96,700,000	$541,000	$1,900,000	$16,400,000	$39,700,000
Average Annual Implementation Cost[b]	$73,600	$19,300,000	$108,000	$380,000	$3,290,000	$7,940,000
Average Annual Cost per Household that gets information on their household water quality[c]	$1,250	$1,860	$275	$878	$2,780	$75
By Payer						
Federal Government	$4	N/A	N/A	$234	N/A	N/A
State Government	N/A	$26	$208	N/A	N/A	N/A
Local Government	N/A	$243	$11	N/A	$1,510	$75
Nonprofit	$1,210	N/A	N/A	N/A	N/A	N/A
Industry	N/A	N/A	N/A	$14	N/A	N/A
Family/Individual	$34	$1,590	$55	$631	$1,270	$0.12
Average Annual Cost per Household adopting water treatment strategy[c]	$4,090	$23,800	$1,310	$8,770	$4,470	$94

[a] Additional details on assumptions, data sources, and projected outcomes are found in Appendix A1.2-3, A2.2-3, A3.2-3, A4.2-3 A5.2-3, A6.2-3.
[b] Average Annual Implementation Cost: Total cost over 5 years divided by 5.
[c] Average Annual Cost Per Household: Average annual implementation cost divided by the number of households reached in the first year.

the average annual implementation costs overall, and per household that gets information about their water quality, regardless of whether they need mitigation of a water contaminant. Average annual cost per household that received information about their water quality ranged from $75 to $2,780. Data presented by payer (in several categories) suggest that the household's average annual cost would range from $0.12 to $1,590, depending on the strategy. The annual implementation cost (for all payers) per household that gets information about their water quality and is projected to adopt a water treatment mitigation strategy ranges from $94 to $23,800.

4. Discussion

This study identified six strategies that represent policy and programmatic options to address three contaminants, including lead, nitrates, and arsenic, in household drinking water sources, including community water systems and private wells. The projected number of households that could learn about the need to address their drinking water quality would be greatest in state-level or community water system-wide strategies such as those in New Jersey, Denver, CO, or Cincinnati, OH. However, the estimated proportion of that total population that also represents a household with low income and young children varied. The proportion of households anticipated to require mitigation varied from 100 percent among populations served by lead-containing community water system infrastructure (Denver and Cincinnati) to 11 to 42 percent of households where contaminants were identified through drinking water testing in private wells. Proven mitigation treatments depended on the contaminant and drinking source and included point-of-use or point-of-entry devices, lead service line replacement, bottled water, or filter pitchers. Household-level adoption of proven mitigation strategies was estimated to range from 62 to 80 percent among households that were the focus of outreach efforts or where water quality testing identified contaminants. The annual cost to implement the strategy per household provided with information on their drinking water quality had a wide range ($75 to $2,780), with the cost borne by individual households ranging from less than $1 (Denver) to $1,590 (New Jersey), indicating that some strategies may surpass the means of families with low incomes.

Researchers found variation between cases in the proportion of households that would need to implement mitigation strategies to remove harmful contaminants from their drinking water (from 11 to 100 percent) due to contaminants in well water sources versus unsafe water service infrastructure (Table 2). In the cases of Denver and Cincinnati, lead infrastructure found throughout the community water systems' supply lines resulted in a widespread need for mitigation at the household level to reduce risks of exposure to lead. Local policy and community water system-wide strategies were necessary to reach the affected community, including households with low incomes and young children. The difference in cost per household between Cincinnati and Denver projections highlights the variability in upfront costs between interim (i.e., filter distribution) and long-term solutions (i.e., replacement of lead service lines). However, upfront costs of such long-term solutions may decrease due to efficiencies, and the benefits are lasting. Lead service lines within community water systems are widespread in the US (Cornwell et al., 2016) and removal costs remain a primary barrier to proactive replacement (US Environmental Protection Agency, 2019).

In cases focused on private wells, observed variations in needed remediation were due to local levels of arsenic or nitrates in water drawn into the wells. These environmental contaminants can occur due to local geology, but are also deposited through human activities, including industrial or agricultural practices (Centers for Disease Control and Prevention). The policy strategy used to promote well water quality testing in New Jersey had a broader population reach than in the New Hampshire WIC-based program, where the focus was on young children in families with low incomes. The cost per household is estimated to be higher in New Jersey as the remediation practices include more costly treatments like reverse osmosis than the less costly filter pitchers supplied in New Hampshire. Strategies that built upon relationships with existing community institutions serving households with young children and low incomes were disproportionately successful in reaching this focus population, providing information, resources, and proven mitigation strategies they might use to protect their health.

A sizable proportion of US households (7.3 percent) in 2015 perceived tap water as unsafe, with the highest proportions found among Hispanic residents (16.4 percent) (Javidi and Pierce, 2018). The use of bottled water varies (Gorelick et al., 2011; Javidi and Pierce, 2018). Researchers estimated the costs of multiple, proven mitigation strategies ranging from infrastructure improvements replacing lead-containing materials, filtration, and in some cases, provision of bottled water where other mitigation strategies could not reliably reduce risks. However, bottled water is costly and in this study it contributes to the estimated cost per household in the cases in Porterville, New Jersey and via Healthcare Clinics. Ideally, successful approaches to support access to quality home drinking water could reduce the economic burden on families that rely on bottled water purchases (Gorelick et al., 2011). Efforts to support safe home tap water could also have additional health benefits, potentially by promoting intake of beverages with less sugar (Reese et al., 2023). Future studies could evaluate the cost and effectiveness of program elements that may address barriers preventing full adoption of proven mitigation strategies (adoption in these cases ranged from 62 to 80 percent). This is particularly relevant for families with low incomes and young children who lack financial resources to maintain higher-cost mitigation actions.

4.1. Study considerations

Cases were purposely selected to provide examples that focused on three harmful drinking water contaminants and varied drinking water sources, providing comparisons of options that could be used to improve access to safe drinking water in the homes of families with young children. However, these cases (and their reach, activities, costs, and impacts) may not be representative of similar initiatives in other geographic locales due to variations such as program participation and local water quality or source. Researchers reported costs by implementation activity, not implementation phase, as suggested by some guidance (Gold et al., 2022). However, the presentation allows for a comparison of diverse initiatives across similar activity categories. The time horizon used in this analysis reflects a researcher-selected period of 5 years. Projections of costs and population reached rely on assumptions based on each case's program and policy data available at the time of the study and estimates from other published data. Data on program costs were derived from multiple sources, including program budget reports, public records, and researcher-derived valuation based on recommended economic evaluation practices. In some cases, data did not allow for detailed accounting for all activities and estimates may not represent all program implementation costs.

4.2. Public health impact

While local drinking water sources, contaminants, and context will vary, this study identified six local strategies representing a range of policy and programmatic options to address lead, nitrates, and arsenic in household drinking water sourced from community water systems and private wells that could be employed by US states and communities. These findings provide a playbook for local decisionmakers to identify actions and resources necessary to increase access to safe drinking water, particularly in homes of families with low incomes and young children.

CRediT authorship contribution statement

A.L. Cradock: Conceptualization, Methodology, Validation, Investigation, Funding acquisition, Formal analysis, Writing – original draft, Visualization, Data curation, Supervision, Project administration, Resources. **J.L. Barrett:** Methodology, Investigation, Writing – review & editing, Formal analysis, Data curation. **E. Nink:** Writing – review & editing, Methodology, Data curation. **C. Wilking:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data that were not confidential are available and noted in the supplementary materials.

Acknowledgments

Funding: This work was supported by a grant from the Robert Wood Johnson Foundation (#76333) and in part by funding from the Centers for Disease Control and Prevention (U48-DP006376). The views expressed are those of the authors and do not necessarily reflect those of any funding agency.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pmedr.2024.102588.

References

Allaire, M., Wu, H., Lall, U., 2018. National trends in drinking water quality violations. Proc Natl Acad Sci USA 115 (9), 2078–2083. https://doi.org/10.1073/pnas.1719805115.

Anand, S.S., Atkinson, S., Davis, A.D., et al., 2007. A family-based intervention to promote healthy lifestyles in an aboriginal community in Canada. Canadian Journal of Public Health-Revue Canadienne De Sante Publique 98 (6), 447–452. https://doi.org/10.1007/BF03405436.

Balazs, C.L., Ray, I., 2014. The Drinking Water Disparities Framework: On the Origins and Persistence of Inequities in Exposure. Article. Am J Public Health. Apr 104 (4), 603–611. https://doi.org/10.2105/ajph.2013.301664.

Centers for Disease Control and Prevention, 2010. *Guidelines for the identification and management of lead exposure in pregnant and lactating women*. US Dept of Health and Human Services. Accessed Oct 19, 2022. https://www.cdc.gov/nceh/lead/docs/publications/leadandpregnancy2010.pdf.

Centers for Disease Control and Prevention. Chemicals That Can Contaminate Tap Water. Centers for Disease Control and Prevention, US Department of Health and Human Services. Mar 9, 2023. Updated Aug 23. 2022. https://www.cdc.gov/healthywater/drinking/contamination/chemicals.html.

Cornwell, D.A., Brown, R.A., Via, S.H., 2016. National survey of lead service line occurrence. J. - Am. Water Works Assoc. 108, E182–E191. https://doi.org/10.5942/jawwa.2016.108.0086.

Dopp, A.R., Mundey, P., Beasley, L.O., Silovsky, J.F., Eisenberg, D., 2019. Mixed-method approaches to strengthen economic evaluations in implementation research. Implement Sci. 14 (1), 2. https://doi.org/10.1186/s13012-018-0850-6.

Edwards, M., Triantafyllidou, S., Best, D., 2009. Elevated blood lead in young children due to lead-contaminated drinking water: Washington, DC, 2001–2004. Environ Sci Technol. 43 (5), 1618–1623. https://doi.org/10.1021/es802789w.

Gold, H.T., McDermott, C., Hoomans, T., Wagner, T.H., 2022. Cost data in implementation science: categories and approaches to costing. Implement Sci. 17 (1), 11. https://doi.org/10.1186/s13012-021-01172-6.

Gorelick, M.H., Gould, L., Nimmer, M., et al., 2011. Perceptions about water and increased use of bottled water in minority children. Arch Pediatr Adolesc Med. 165 (10), 928–932. https://doi.org/10.1001/archpediatrics.2011.83.

Javidi, A., Pierce, G., 2018. U.S. Households' Perception of Drinking Water as Unsafe and Its Consequences: Examining Alternative Choices to the Tap. Water Resources Research 54 (9). https://doi.org/10.1029/2017WR022186.

Johnson, T.D., Belitz, K., Lombard, M.A., 2019. Estimating domestic well locations and populations served in the contiguous U.S. for years 2000 and 2010. Sci Total Environ. 687, 1261–1273. https://doi.org/10.1016/j.scitotenv.2019.06.036.

Kumanyika, S.K., 2019. A framework for increasing equity impact in obesity prevention. Am J Public Health. 109 (10), 1350–1357. https://doi.org/10.2105/ajph.2019.305221.

Lahlou, S., Boesen-Mariani, S., Franks, B., Guelinckx, I., 2015. Increasing water intake of children and parents in the family setting: a randomized, controlled intervention using installation theory. Annals of Nutrition and Metabolism 66, 26–30. https://doi.org/10.1159/000381243.

Levin, R., Villanueva, C.M., Beene, D., et al., 2023. US drinking water quality: exposure risk profiles for seven legacy and emerging contaminants. Review; early access. Journal of Exposure Science and Environmental Epidemiology 20. https://doi.org/10.1038/s41370-023-00597-z.

McDonald, Y.J., Jones, N.E., 2018. Drinking Water Violations and Environmental Justice in the United States, 2011–2015. Am J Public Health 108 (10), 1401–1407. https://doi.org/10.2105/ajph.2018.304621.

McGowan, L., Cooke, L.J., Gardner, B., Beeken, R.J., Croker, H., Wardle, J., 2013. Healthy feeding habits: efficacy results from a cluster-randomized, controlled exploratory trial of a novel, habit-based intervention with parents. American Journal of Clinical Nutrition 98 (3), 769–777. https://doi.org/10.3945/ajcn.112.052159.

Muckelbauer, R., Gortmaker, S.L., Libuda, L., et al., 2016. Changes in water and sugar-containing beverage consumption and body weight outcomes in children. Br J Nutr. 115 (11), 2057–2066. https://doi.org/10.1017/s0007114516001136.

Patel, A.I., Hecht, C.E., Cradock, A., Edwards, M.A., Ritchie, L.D., 2020. Drinking Water in the United States: Implications of Water Safety, Access, and Consumption. Annu. Rev. Nutr. 40, 345–373. https://doi.org/10.1146/annurev-nutr-122319-035707.

Pieper, K.J., Katner, A., Kriss, R., Tang, M., Edwards, M.A., 2019. Understanding lead in water and avoidance strategies: a United States perspective for informed decision-making. Journal of Water and Health 17 (4), 540–555. https://doi.org/10.2166/wh.2019.272.

Popkin, B.M., D'Anci, K.E., Rosenberg, I.H., 2010. Water, hydration, and health. Nutr. Rev. 68 (8), 439–458. https://doi.org/10.1111/j.1753-4887.2010.00304.x.

Reese, A.C., Burgos-Gil, R., Cleary, S.D., et al., 2023. Use of a water filter at home reduces sugary drink consumption among parents and infants/toddlers in a predominantly hispanic community: results from the water up!@ home intervention trial. J Acad Nutr Diet. 123 (1), 41–51. https://doi.org/10.1016/j.jand.2022.06.006.

Rogan, W.J., Brady, M.T., 2009. Drinking water from private wells and risks to children. Pediatrics 123 (6), e1123–e1137. https://doi.org/10.1542/peds.2009-0752.

Sanders, G.D., Neumann, P.J., Basu, A., et al., 2016. Recommendations for conduct, methodological practices, and reporting of cost-effectiveness analyses: second panel on cost-effectiveness in health and medicine. JAMA 316 (10), 1093–1103. https://doi.org/10.1001/jama.2016.12195.

Sherris, A.R., Baiocchi, M., Fendorf, S., Luby, S.P., Yang, W., Shaw, G.M., 2021. Nitrate in drinking water during pregnancy and spontaneous preterm birth: a retrospective within-mother analysis in California. Environ Health Perspect. 129 (5), 57001. https://doi.org/10.1289/ehp8205.

US Environmental Protection Agency, 2012. *Integrated Science Assessment (ISA) for Lead (Third External Review Draft, Nov 2012)*. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-10/075C, 2012.

US Department of Agriculture, 2019. Infant Nutrition and Feeding: A Guide for Use in the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC). FNS-826. Accessed Mar 10, 2023. https://wicworks.fns.usda.gov/resources/infant-nutrition-and-feeding-guide.

US Environmental Protection Agency, 2019. *Strategies to Achieve Full Lead Service Line Replacement*. EPA 810-R-19-003. Accessed Mar 9, 2023. https://www.epa.gov/ground-water-and-drinking-water/strategies-achieve-full-lead-service-line-replacement.

US Environmental Protection Agency. Environments and contaminants – drinking water contaminants. US Environmental Protection Agency. Updated Oct 25, 2022. Accessed Mar 9, 2023. https://www.epa.gov/americaschildrenenvironment/environments-and-contaminants-drinking-water-contaminants.

Wilking, C., Nink, E., Cradock, A.L., 2022. Safe Home Water: Executive Summary and Detailed Case Study Briefs. Boston, MA: Prevention Research Center on Nutrition and Physical Activity at the Harvard T.H. Chan School of Public Health. Accessed Mar 10, 2023. https://www.hsph.harvard.edu/prc/projects/safe-home-water.