PLOS WATER

RESEARCH ARTICLE

Analyzing multiple-source water usage patterns and affordability in rural Central Appalachia

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Data availability statement: This study collected individual-level survey data from a small group of participants from vulnerable populations. Hence, the data are restricted by Virginia Tech's Institutional Review Board (IRB) and are not accessible to the public or research community. Contact information for the Virginia Tech IRB can be found here: https://www.research.vt.edu/sirc/hrpp/index.html. All recruitment methods, community partnerships, and research procedures were pre-approved and overseen by the Virginia Tech Institutional Review Board (VT IRB #22-599).

Abstract

Nearly 500,000 American households lack complete plumbing, and more than 21 million Americans are reliant on public drinking water systems with at least one annual health-based drinking water violation. Rural, low-income, and minority communities are significantly more likely to experience unavailable or unsafe in-home drinking water. Lack of access and distrust of the perceived quality of municipally supplied water are leading an increasing number of Americans to rely instead on less regulated, more expensive, and potentially environmentally detrimental water sources, such as roadside springs and bottled water. Previous research studies have stressed the importance of considering the economic burden of all water-related expenditures, including financial and non-financial water-related costs; however, past examinations of water costs have primarily focused on municipal water supplies. We propose an economic model to consider the full economic burden associated with multiple-source water use by incorporating both direct costs (e.g., utility bills, well maintenance, bottled water purchase, payments for water hauling/delivery) and indirect water-related expenditures (e.g., transportation costs to gather water, productivity lost due to time spent collecting). Using data gathered from household surveys along with the economic model, this study estimates the economic burden from two case studies in rural Central Appalachia with persistent water quality concerns: (1) McDowell County, WV (n = 15) and (2) Letcher and Harlan Counties, KY (n = 9). All surveyed households (n = 24) rely on multiple sources of water to meet their needs, frequently citing their perception of unsafe in-home tap water. Bottled water was the most common choice for drinking water in both settings (92%, n = 24), though roadside spring use was also prevalent in McDowell County, WV (53%, n = 15). The results show that multiple-water source use is associated with a large economic burden. Households reliant primarily on bottled water as their drinking water source spent 10.3% (McDowell County, WV) and 5.3% (Letcher and Harlan Counties, KY) of their respective county's median household income (MHI) on

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water-related expenditures. Households reliant primarily on roadside springs as their drinking water source spent 6.4% (McDowell County, WV) of MHI on water-related expenditures. Hence, the majority of participating households (75%, n = 24) spend above the US water affordability threshold of 2% MHI. The application of this economic model highlights substantial water affordability concerns in water-insecure Appalachian communities and provides a foundation for future studies and enhancements.

Introduction

Safe drinking water insecurity and inequality in the US

Issues related to drinking water safety persist in the United States. Nearly 500,000 American households lack complete plumbing, meaning they lack either (1) hot and cold running water, (2) a sink with a faucet, (3) a bath or a shower, or some combination [1]. Recent analyses have revealed that more than 1,000 community water systems do not consistently achieve the water quality and monitoring requirements of the US Safe Drinking Water Act (SDWA) [1]; this translates to an estimate of more than 21 million Americans who are reliant on public drinking water systems with at least one annual health-based drinking water violation [2]. Apart from those reliant on federally regulated water sources (i.e., municipal water supplies), an additional 23 million American households rely on private, unregulated drinking water wells [3]. As the responsibility of all monitoring and maintenance is left to homeowners, private water sources have increased risk for contamination and reliability concerns [4–10].

Increasing evidence suggests that reliable water access is not distributed equally in the US. Socioeconomic factors consistent with well-recognized social inequalities including education, poverty, age, and race/ethnicity are associated with higher rates of incomplete plumbing and/or higher risk of water quality violations [1,11–14]. Rurality is also highly predictive of challenges to safe household water access both because violations of public drinking water systems are spatially clustered in rural communities [2], and because reliance on unregulated private water systems is higher in rural regions [3,4,15].

Rise of bottled water reliance

The recent increase in bottled water use in American homes is complex, but has been primarily attributed to lack of access to and distrust of in-home tap water [16–18]. US sales of bottled water have increased more than twofold, from 6 billion gallons purchased in 2001 to 15 billion gallons totaling $36.2 billion in 2020 [17]. In addition to negative environmental impacts at the source, high energy costs associated with processing and transportation, and plastic waste [16,19–22], bottled water represents a large financial cost for reliant homes. Estimates suggest bottled water is 500 to 1,000 times more expensive than municipal drinking water [19]. Given that low-income communities are more likely to struggle with issues of poor in-home water quality, the financial cost encountered by communities reliant on bottled water is significant [16].

Multiple-source water use in Central Appalachia

Central Appalachia is widely recognized as a region of water insecurity in the US [1,23–27]. Previous work has documented in-home water quality issues in point-of-use water samples, including the presence of health-based contaminants such as fecal indicator bacteria (e.g., E. coli), heavy metals (e.g., Pb, Fe), and radon, as well as elevated concentrations of metals associated with aesthetic issues [9,25,26,28,29]. Somewhat unique to the region, some residents rely wholly or partially on roadside springs, despite widespread contamination, to meet household needs [25,30–32]. Consistent with trends at the national level, to avoid poor in-home water quality, bottled water reliance is also quite common [33–36]. The associated economic burden with bottled water reliance has yet to be quantified. This study aims to quantify the expenditures associated with meeting household needs through multiple-source water use in Central Appalachia through two case studies: (1) McDowell County, West Virginia (WV) and (2) Letcher and Harlan Counties, Kentucky (KY).

Quantifying affordability

United Nations (UN) Sustainable Development Goal 6 (SDG6) calls for safe and affordable water for all by 2030 [37]; however, the definition of "affordability" is not provided, and has resulted in notable debate [38–40]. Previous work most commonly relies on affordability ratios comparing water costs as a percentage of income, typically using thresholds established by national governments or international organizations [38,41–44]. In the US, a 2% median household income (MHI) threshold is often cited, while international organizations such as the United Nations Development Programme, World Bank, and Organisation for Economic Co-operation and Development (OECD) have established thresholds between 3% and 5% of MHI [38,39,43,45,46].

While the affordability threshold as a percentage of MHI allows for standardized comparisons and is easy to communicate, it has limitations. The use of a fixed threshold imposes a rigid binary (e.g., 2.1% is considered unaffordable, while 1.9% is not), even when households facing these conditions may experience similar challenges [40,47]. Further, crossing an affordability threshold does not necessarily indicate equitable access within or across communities [48], nor does this approach account for dimensions of accessibility [38]. Alternative affordability metrics have been proposed to address these limitations. These include measuring the cost of a basic volume of water to meet essential needs, comparing water bills to other utility costs, estimating affordability in terms of days of labor, or comparing costs to disposable rather than gross income [38,40,41,43,47]. Others advocate for a multidimensional framework that combines several metrics for a more comprehensive assessment [49].

In this analysis, we use the 2% MHI threshold as a benchmark due to its policy relevance in the US and comparability with existing studies. We intend for this threshold to be understood as a general indicator rather than a definitive measure, drawing attention to the overall burden associated with water insecurity and multiple-source water use in rural Central Appalachia. Our contribution builds on existing work by accounting for both direct and indirect costs of household water acquisition and by extending affordability analysis beyond municipally supplied piped water.

Although multiple works have stressed the importance of considering all water-related expenditures including financial and non-financial water-related costs, the data-intensive nature of such analyses renders this a challenging task [38,41,43]. Critically, past examinations of water costs have primarily focused on municipal water supplies alone; there are no available cost estimates even for the established practice of well water use [41]. In keeping with previous recommendations, this effort creates an economic model of water affordability, considering not a sole source, but the entire range of water sources used to meet household needs in rural settings, including municipal, well, bottled, and spring sources as well as taking into account both direct (e.g., purchase, payments) and indirect (e.g., transportation, productivity lost) expenditures related to the multiple-source water use.

Research settings

Given our intention to assess multiple-source water use and affordability in low-income rural households, we focused our research on two case study communities in the Central Appalachian subregion of the United States (Fig 1). This subregion, as defined by the Appalachian Regional Commission, is particularly associated with environmental health disparities and severe poverty [23,50,51]. McDowell County, WV, is the third poorest county in the US [52], with a 2022 median household income of $28,235 and 37.6% of residents living below the national poverty line [53]. Though slightly less severe, conditions in the Kentucky setting also reflect significant challenges. Letcher County has a median household income of $38,466 and 28.7% of residents live below the national poverty line [53]. Harlan County has a median household income $35,128 and 26.9% of residents live below the national poverty line [53]. The following analyses cluster these into two case studies: (1) McDowell County, WV, (n = 15) and (2) Letcher and Harlan Counties, KY, (n = 9).

Methods

Ethics statement

This study uses findings obtained from distributed questionnaires to human participants. All recruitment methods, community partnerships, and research procedures were pre-approved and overseen by the Virginia Tech Institutional Review Board (VT IRB approval number

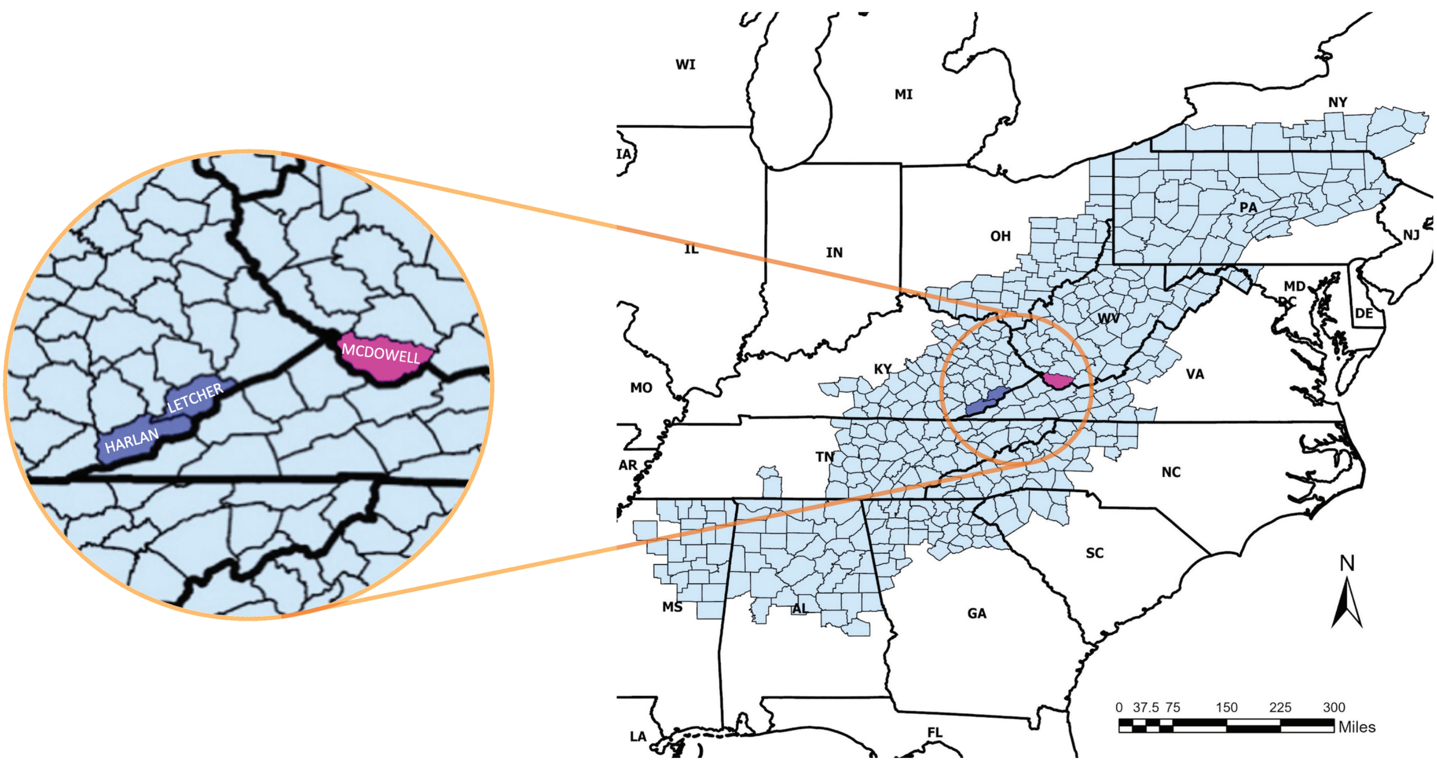

Fig 1. Research settings map. Map of the Appalachian region with McDowell County, WV, highlighted in pink and Letcher and Harlan Counties, KY, highlighted in blue.

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#22-599). The recruitment period started on September 1, 2022, and ended on November 8, 2023. Informed consent was obtained from all participants via written consent forms.

Household recruitment and community partnerships

Participating households were recruited in partnership with local nonprofit organizations (Dig Deep Inc. and God's Outreach Center in West Virginia and Headwaters Inc. in Kentucky). Households represented families already working in partnership with the local nonprofits or friends and neighbors of those households who learned about the research study and expressed interest in participating.

All participants completed a survey detailing use, perceptions, motivations, and expenditures (both time and money) related to in-home piped water, bottled water, and roadside spring use, if applicable. The data were collected in McDowell County, WV, in November 2022 and in Letcher and Harlan Counties, KY, in November 2023. Questions were adapted from those used in Cohen et al. [10,54] and in-brief addressed:

- demographics (i.e., racial identification, homeowner status, household income range, education level, marital status),
- specific water use behaviors (i.e., primary drinking water source, secondary drinking water source, primary cooking water source, primary bathing water source);
- financial costs (i.e., average water bill cost, cost of annual spring or private well maintenance, sewage costs, average electricity bill cost);
- behaviors and perceptions related to water quality (point-of-use water treatment habits and reasoning, perceptions of household non-bottled water quality, primary and secondary issues with households' water source);
- bottled water information (i.e., reasoning for consuming bottled water, size of bottle, frequency of purchase, go-to brand, estimated expenditure on bottled water purchase, store of purchase, distance from store);
- roadside spring information (i.e., reasoning for consuming roadside spring water, distance from roadside spring, frequency of collection);
- well-being (i.e., frequency of non-serious illness, frequency of serious illness, change in health of community);
- other (sweet beverage consumption, stain remover purchase, availability of hot running water, whether plumbing is complete (functioning toilet, sink, and shower), sewage type, septic tank maintenance, essential water uses).

For their participation in the study, households received free in-home water quality testing and analysis. Though the present study addresses the economic analysis, water quality results were analyzed and are thoroughly described by Albi et al. [28]. Relevant trends are discussed briefly in Results and discussion. The scope of this paper aims to characterize typical water usage patterns between sources and assess water affordability by considering recurring direct costs (e.g., purchase, payments) and indirect costs (e.g., transportation, productivity lost) associated with different sources.

Measuring affordability

We measured affordability using expenditures as a share of annual median household income (MHI) in each respective county as reported by the US Census Bureau and compared the results to the US affordability threshold of 2% [43,45,53]. We aimed to consider the full economic burden by measuring both financial direct costs (i.e., utility bills, well maintenance, bottled water purchase, payments for water hauling/delivery) and non-financial indirect water-related expenditures (i.e., transportation costs to gather water, productivity lost due to time spent collecting).

Data analysis

In this study, a set S of water sources is evaluated, including utility $(U \in S)$, private wells $(W \in S)$, bottled water $(B \in S)$, and roadside springs $(R \in S)$. For an individual residence or household, i, the objective was to estimate the cost (c_{is}) of obtaining water from each source used. One of the aims of this study was to integrate both direct costs (d_{is}) and indirect costs (n_{is}) for each residence and water source, such that

$$c_{is} = d_{is} + n_{is}.$$

The recurring annual costs for each resident to obtain water from all sources were estimated as follows:

$$C_i = \sum_{s \in S} c_{is}.$$

For each household, the reported ***direct costs*** (financial water-related data) were converted into average annual payments per household. The potential direct costs include utility bill payments (u_{is}), maintenance costs for wells or other infrastructure (m_{is}), purchase costs of bottled water (p_{is}), and direct delivery or haulage costs (h_{is}). Reports of routinely paying a person outside the household for bottled water or roadside spring deliveries were considered direct costs. Thus, the direct costs for each residence and water source were estimated as follows:

$$d_{is} = u_{is} + p_{is} + m_{is} + h_{is}.$$

The ***indirect costs*** considered in this study include personal transportation costs (t_{is}) and potential productivity losses (l_{is}). These costs, which were not reported by the participants, were estimated using households' reported frequency of visits and reported duration of travel time along with publicly available data on average at-home food expenditures, state gas prices, average miles per gallon in the US, and state minimum wage rates. Thus, the indirect costs for each residence and water source were estimated as follows:

$$n_{is} = t_{is} + l_{is}.$$

Respondents reported the time from their residence to local stores and roadside springs in minutes spent on a one-way trip. We converted this time spent on a one-way trip to total hours spent traveling per year to a source (a_{is}) by using their reported frequency of visiting the store or roadside spring, considering round trip distances, and converting these minutes to hours.

For trips to purchase bottled water, we assume that households are purchasing other food items on the same trip. To account for this, we adjust the total reported hours spent traveling to the store for bottled water annually (a_{iB}) by the fraction of total grocery expenses attributable to bottled water (f_{iB}). This fraction (f_{iB}) is estimated by dividing each household's reported annual bottled water purchases (p_{iB}) by the average annual at-home food expense associated with their respective county MHI (v_i). Thus, the fraction of travel time to the store attributed to bottled water acquisition is estimated by $f_{iB} = \min(\frac{p_{iB}}{v_i}, 1)$. Average at-home food expenditures (v_i), which include non-alcoholic beverages, are provided by the US Bureau of Labor Statistics Consumer Expenditure Surveys by household income before taxes at the national level [55]. McDowell County, WV, with a median household income of $28,235 fell into the $15,000-$29,999 household income bracket with an average annual spending on at-home food of $3,624. Letcher and Harlan Counties, KY, with median household incomes of $38,466 and $35,128, respectively, fell into the $30,000-$39,999 household income bracket with an average annual spending on at-home food of $4,430. Hence, the adjusted total hours spent traveling per year to a source is given by $y_{is} = a_{is} \times f_{is}$ where $f_{iB} = \min(\frac{p_{iB}}{v_i}, 1)$ for bottled water and $f_{iR} = 1$ for roadside springs.

Transportation costs were estimated for trips to a store to purchase bottled water and trips to the roadside spring to haul water. We estimated yearly mileage (m_{is}) by estimating the average speed (s_i) that each resident could travel on such trips, such that $m_{is} = y_{is} \times s_i$. For this study, we used $s_i = 45$ miles per hour due to the rural locations of residents. For these settings, we assumed the residents were using gasoline powered vehicles. Thus, we converted the yearly mileage into the annual cost of gas for traveling to obtain bottled water or travel to haul roadside spring water by using the 2022 average US light duty vehicle efficiency ($e = 22.8$ miles per gallon) [56] and the yearly average of the price of regular gas per gallon (g_i) in the respective state ($3.40 for residences in WV and $3.16 for residences in KY) [57]. Thus, the transportation cost is estimated by $t_{is} = m_{is} \times \frac{g_i}{e}$.

Similarly, to quantify productivity lost traveling to each source (l_{is}) we followed the World Health Organization's (WHO) guide, comparing the opportunity cost of time to the minimum wage rate [58]. Productivity losses were estimated using the time lost for roundtrip travel to the store for bottled water purchases and the roadside springs. We converted the adjusted hours spent traveling to collect water per year (y_{is}) into productivity losses by using the minimum wage rate (w_i) in the respective state ($8.75 for residences in WV and $7.25 for residences in KY) to estimate the opportunity cost of time spent collecting for working age adults [59]. Thus, the productivity loss is estimated by $l_{is} = w_i \times y_{is}$.

For this study, Table 1 summarizes the types of costs that were reported or estimated for each water source. As shown, some residents hired someone outside their household to haul bottled water or roadside spring water for them and thus incurred a haulage cost (h_{is}). Some residents traveled to purchase bottled water or obtain roadside spring water and thus incurred personal transportation costs (t_{is}) and loss of productivity (l_{is}).

Results and discussion

Survey demographics

Overall, we collected data from 24 households: 15 households in McDowell County, WV, and 9 households in Letcher and Harlan Counties, KY. Of the 15 households recruited in McDowell County, WV, nearly half (47%), reported an annual household income of less than $15,000 (i.e., roughly half the MHI of the county). Approximately 80% of households were below the national poverty line for a family of four, and 80% of households also reported an education

Table 1. Direct and indirect costs associated with each evaluated drinking water source.

	Direct Costs (d_{is})				Indirect Costs (n_{is})	
Source	**Utility bills**	**Maintenance**	**Purchase**	**Haulage**	**Transportation**	**Loss of productivity**
Utility (U)	u_{iU}	–	–	–	–	–
Private well (W)	–	m_{iW}	–	–	–	–
Bottled water (B)	–	–	p_{iB}	h_{iB}	t_{iB}	l_{iB}
Roadside spring (R)	–	–	–	h_{iR}	t_{iR}	l_{iR}

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level of high school or lower. All but one survey respondent identified their race as White alone. In terms of health, 60% reported having a household member sick monthly or more and 60% feel the health of the community has worsened over the last two years.

Though participants in both case studies struggle with water access and water quality concerns, the demographics of participants in Letcher and Harlan Counties, KY, were very different than those in McDowell County. Of the 9 households, two-thirds (67%), reported an annual household income of more than $50,000, which is above the MHI in each of the respective counties. These participants were also more educated: 89% of households also reported continuing education levels beyond high school. All survey respondents identified as White alone. Reported household health was much better than the McDowell County respondents with only 11% reported having a household member sick monthly or more. However, perceptions of community health were similar, with 67% reporting feelings that the health of the community has worsened over the last two years. Differences in participant demographics reflect the different populations currently working with each of the community nonprofit groups.

Water usage patterns

Multiple-source water use was prevalent among all participating households. Fig 2 illustrates the primary and secondary drinking water sources of the participants in each setting. Results from both settings were consistent with previous reports of multiple-source water use being motivated by perceived poor water quality [25,27,30,32]. 73% of participants in McDowell County and 100% of participants in Letcher and Harlan Counties view their non-bottled water quality as satisfactory or less. Therefore, in each setting, all but one respondent reported relying on bottled water as a primary or secondary drinking water source. These findings are consistent with recent reports of increased bottled water reliance from Appalachian communities [24,33–36]. The most frequently cited reason for bottled water use was perception of unsafe tap water.

Notably, in McDowell County, roadside spring reliance was also common, with more than half of participating households collecting roadside spring water as a drinking water source. No roadside spring use was reported in Letcher and Harlan Counties, highlighting another

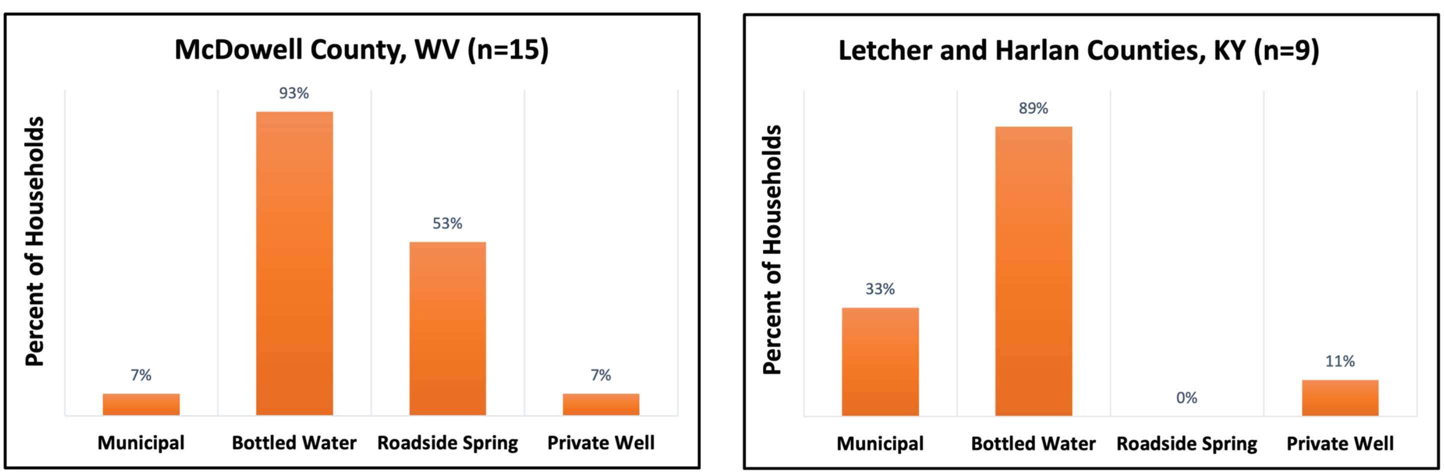

Fig 2. Drinking water sources. McDowell County, West Virginia (left) and Letcher and Harlan Counties, Kentucky (right) primary and secondary drinking water sources.

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major difference from the McDowell County case study. However, the bottled water reliance and perceptions of unsafe tap water showcase that the issues of trust in the public municipal water sources and subsequent reliance on other sources occurred irrespective of income or education level.

Though the present work is focused on quantifying the costs of water in these settings, it is worth noting that point-of-use water quality contamination was not uncommon. Particularly in samples collected in McDowell County, in-home water samples were frequently positive for coliform (83%) and E. coli (33%). A variety of additional contaminants associated with taste and aesthetics (iron, manganese, aluminum) and health (sodium) were detected at concentrations above US Environmental Protection Agency (EPA) standards and guidelines in both well and municipal samples. Bottled water samples did not violate any health-based guidelines. In-home water samples contained detectable per- and polyfluoroalkyl substances (PFAS) compounds, and all in-home, roadside spring, and bottled water samples contained detectable concentrations of microplastics. A complete discussion of water quality data and methodological sampling details is available in Albi et al. [28].

Direct versus indirect water expenditures

In McDowell County, WV, on average, over a third (38%) of household water-related expenditures were indirect costs (i.e., travel costs, lost time), though there was considerable variability between participating households (Fig 3). Regardless of this variability, it is worth noting that the water expenditures exceed the US affordability threshold of 2% of MHI for all but three households (including the household where residents reported drinking their municipally supplied piped water and the household where residents reported drinking from their private well). The high indirect costs reflect both the long travel distances to grocery stores, as well as the frequent use of water hauled from roadside springs. It appears lower income households may offset direct financial payments by substituting monetary payments with more time spent collecting roadside spring water. Critically, if indirect costs were not considered, the low-income households would appear to bear a much smaller economic burden than they face in actuality.

An examination of household expenditures in Letcher and Harlan Counties, KY, differs distinctly from that estimated for McDowell County. On average, only 2% of household water expenditures for the participating households in Kentucky were associated with indirect costs, and the variability in water expenditures as a percentage of MHI was much lower (Fig 4). They also spent a smaller percentage of their respective MHI than the participating households in the McDowell County case study. However, again, expenditures for all but three homes exceeded the US affordability standard of 2%.

Water expenditures by individual expense

Examination of water expenditures broken down by individual expense similarly reveals distinct differences in the sources of expense between the two case study settings (Figs 5 and 6). As mentioned previously, distance to local grocers adds considerable expense to participating households in McDowell County reliant on bottled water. Households reported purchasing bottled water every five days and spending an average of 39 minutes for a one-way trip to the store, which adds considerable time and expense (Fig 5). Though roadside springs are closer (14 minutes one-way), they are generally visited more frequently (every 2–3 days). Frequency of water collection and longer distances contribute to a high indirect cost from gas used and productively lost, especially for more remote households.

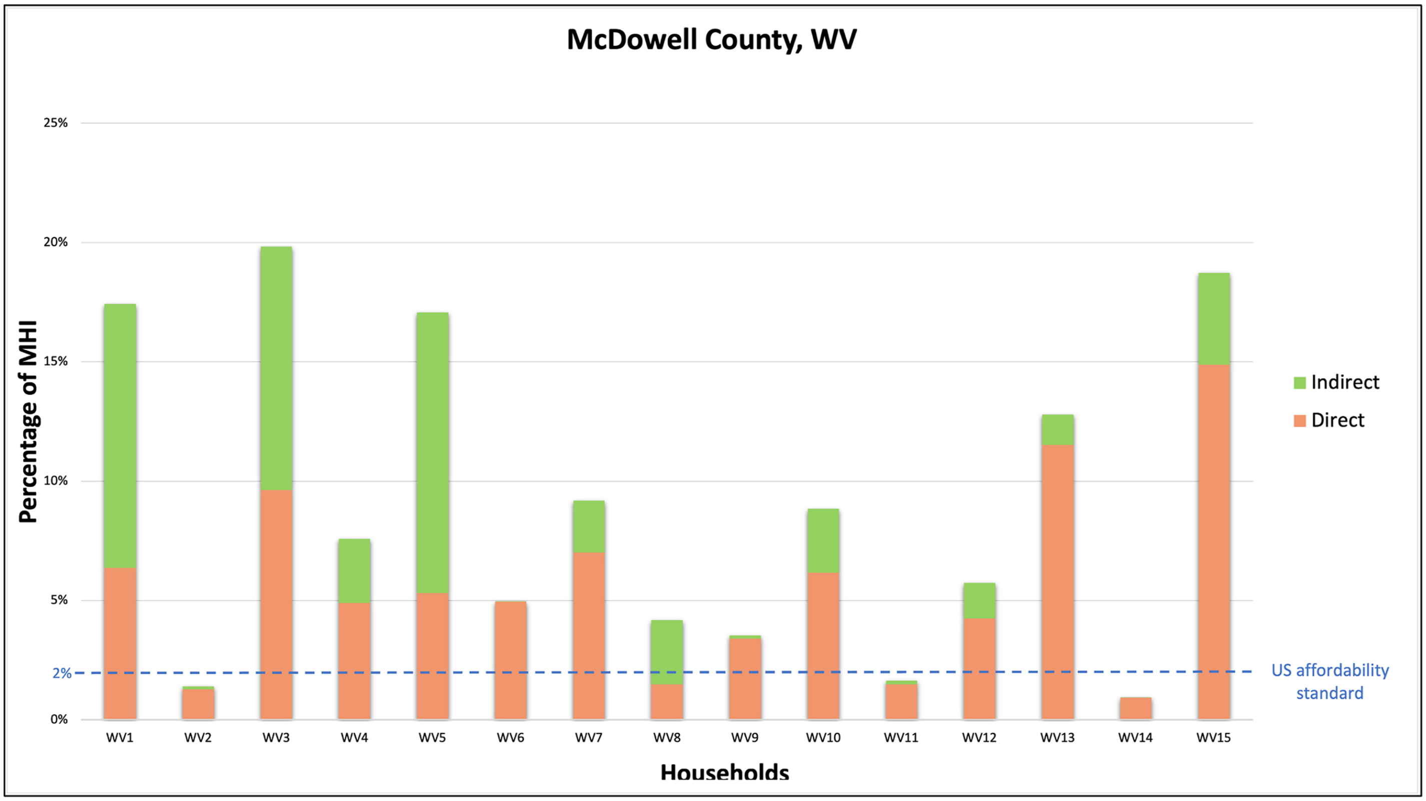

Fig 3. WV direct and indirect expenditures. McDowell County, West Virginia direct versus indirect water expenditures as a percentage of median county household income, ordered from lowest (left) to highest (right) reported household income.

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Though bottled water in-store purchase or at-home delivery still accounted for a large portion of direct costs for households participating in Kentucky (Fig 6), the associated indirect costs from travel were not as extreme. Participants reported an average of 14 minutes one-way travel time to buy bottled water and visited the store for bottled water purchases, on average, once every 10 days. No participating households in Kentucky relied on roadside springs, though a few participants did report annual well maintenance costs which were not reported by the participating households in West Virginia.

Average affordability

Considering annual expenditures by primary drinking water source, households relying on bottled water as their primary drinking water source spent the most on water expenses in both case studies (Fig 7) though the actual amount varied due to differences in amounts purchased, average distance from store, and frequency of visits as discussed above. It should also be noted that the difference in MHI by study area further contributes to differences in percent of expenditures: Letcher and Harlan Counties, KY, have higher respective MHIs ($38,466, $35,128) than McDowell County, WV ($28,235) [53]. In West Virginia, households relying primarily on roadside springs as their drinking water source also spent a large portion of MHI on water expenses (11.8%), reemphasizing the importance of quantifying the total economic burden rather than just direct financial expenditures because roadsides springs have no inherent direct costs. Households reliant primarily on piped water for drinking, in contrast, were

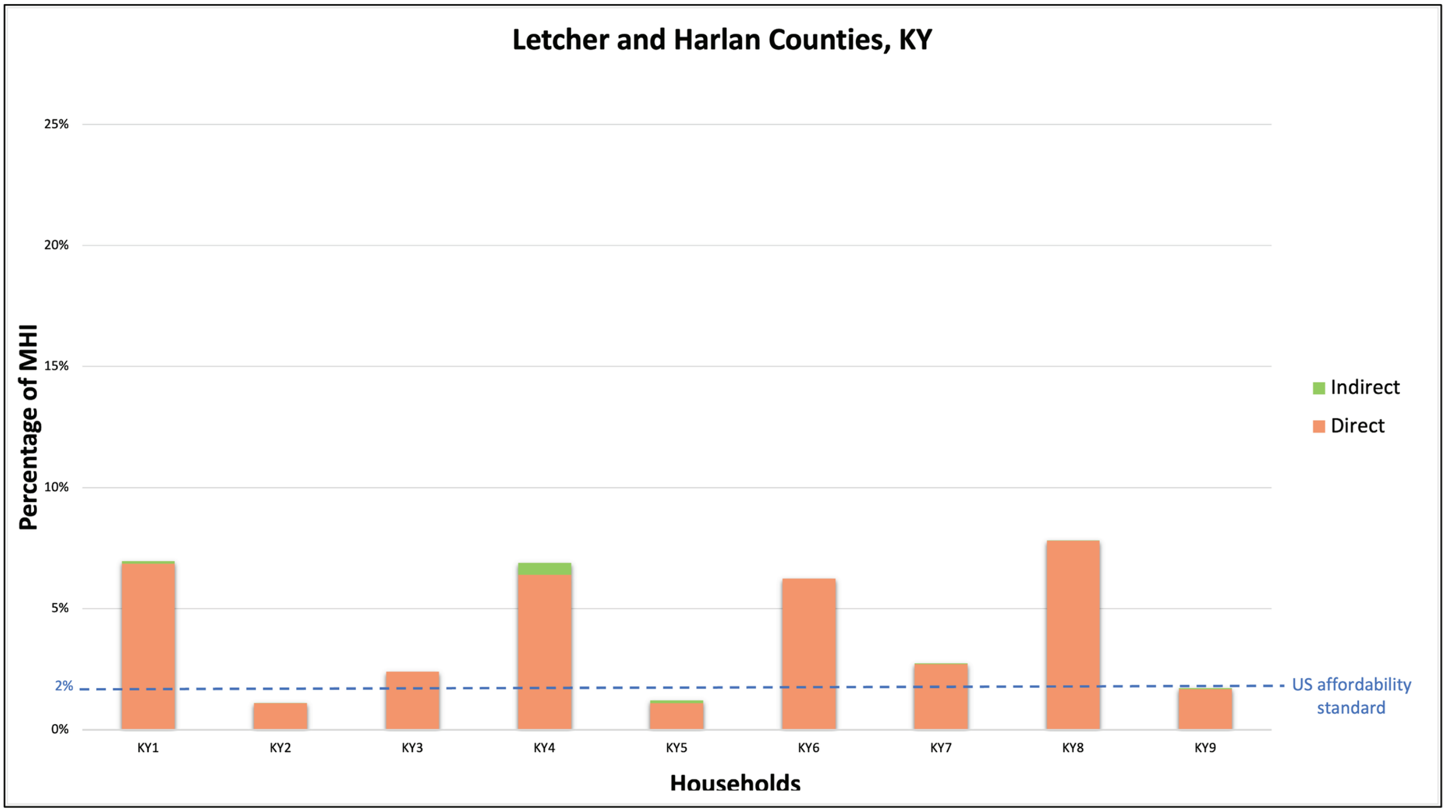

Fig 4. KY direct and indirect expenditures. Letcher and Harlan Counties, Kentucky direct versus indirect water expenditures as a percentage of median county household income, ordered from lowest (left) to highest (right) reported household income.

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below or roughly aligned with the US affordability standard: 1.0% in West Virginia and 2.1% in Kentucky. The one household relying primarily on well water in Kentucky spent just 1.1% of MHI.

Cost of bottled water

All participating households relied on multiple sources of water to meet their household needs, including piped water, bottled water, well water, and in McDowell County, hauled water from roadside springs. Previous work has stressed that bottled water is much more expensive than other sources, so it is notable that bottled water is the beverage of choice in high-poverty communities. Approximately 73% of households in McDowell County, WV, and 67% in Letcher and Harlan Counties, KY, reported relying primarily on bottled water for drinking. As illustrated in Fig 8, average bottled water expenditures alone (i.e., removal of costs associated with well maintenance, utility bills, or roadside spring visits) exceed the US affordability standard of 2% of MHI for those households primarily reliant on bottled water for drinking. Although the WHO currently considers bottled (packaged) water an improved source [60], it is worth considering whether reliance on such an expensive water source during non-crisis time periods is acceptable for high-poverty communities, as lost funds could be invested towards other needs to improve household standards of living and well-being.

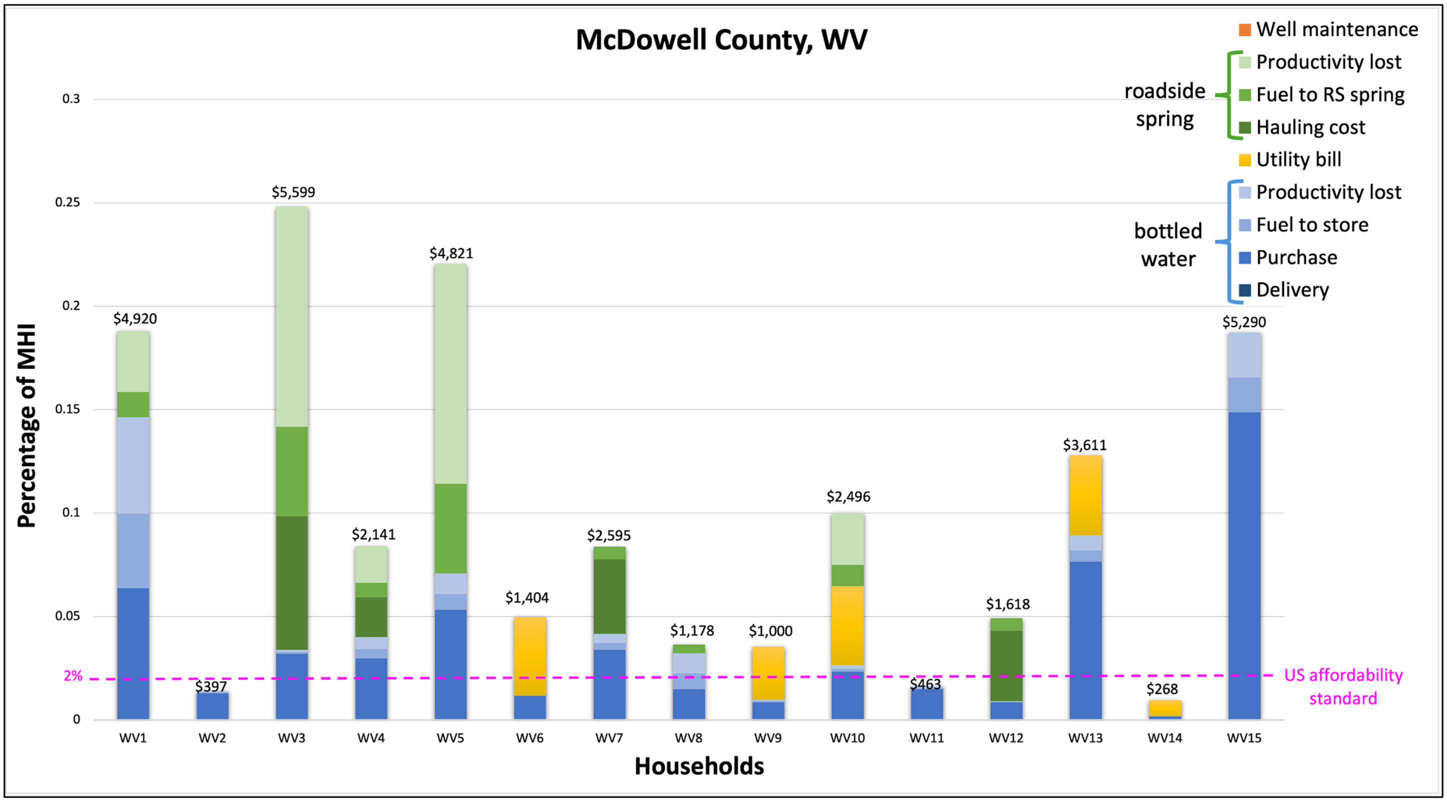

Fig 5. WV total expenditures. McDowell County, West Virginia total water-related expenditures as a percentage of median county household income, ordered from lowest (left) to highest (right) reported household income. Total dollar amount spent by each household on water-related expenditures is presented at the top of each bar.

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Limitations

This study was not designed to be broadly generalizable to rural Appalachian populations or even those residing in the target counties. Given issues of trust, examinations of water insecurity often rely on small samples of convenience within communities. For example, recent published studies examining water security in underserved areas of the United States have reported results from 24 households in an environmental justice neighborhood in North Carolina [7], 24 homes in Central Appalachia reliant on roadside springs [25], 33 households in southwest Appalachian Virginia reliant on public and private drinking water sources [10], and 46 households in the Texas colonias reliant on private wells and water hauling [61]. As in these past studies, the aim of the present work is exploratory: to examine the potential of a new quantification strategy, to build partnerships through community participatory research, and to identify and/or justify future in-depth areas of research. Survey participants are using personal recall periods to report expenditures and frequencies of water collection (average monthly), maintenance (average yearly), and health (average yearly), which has limitations. Unfortunately, the data collected were insufficient to provide much insight into the typical costs of private well maintenance. Six of the 24 participants did indicate that they were at least partially reliant on water piped directly to their home from a private water well, but only two reported annual expenses, which ranged from $300 to $660. This may reflect an inherent variability and unpredictability in average annual well costs, as users may only recall significant expenditures after a major repair.

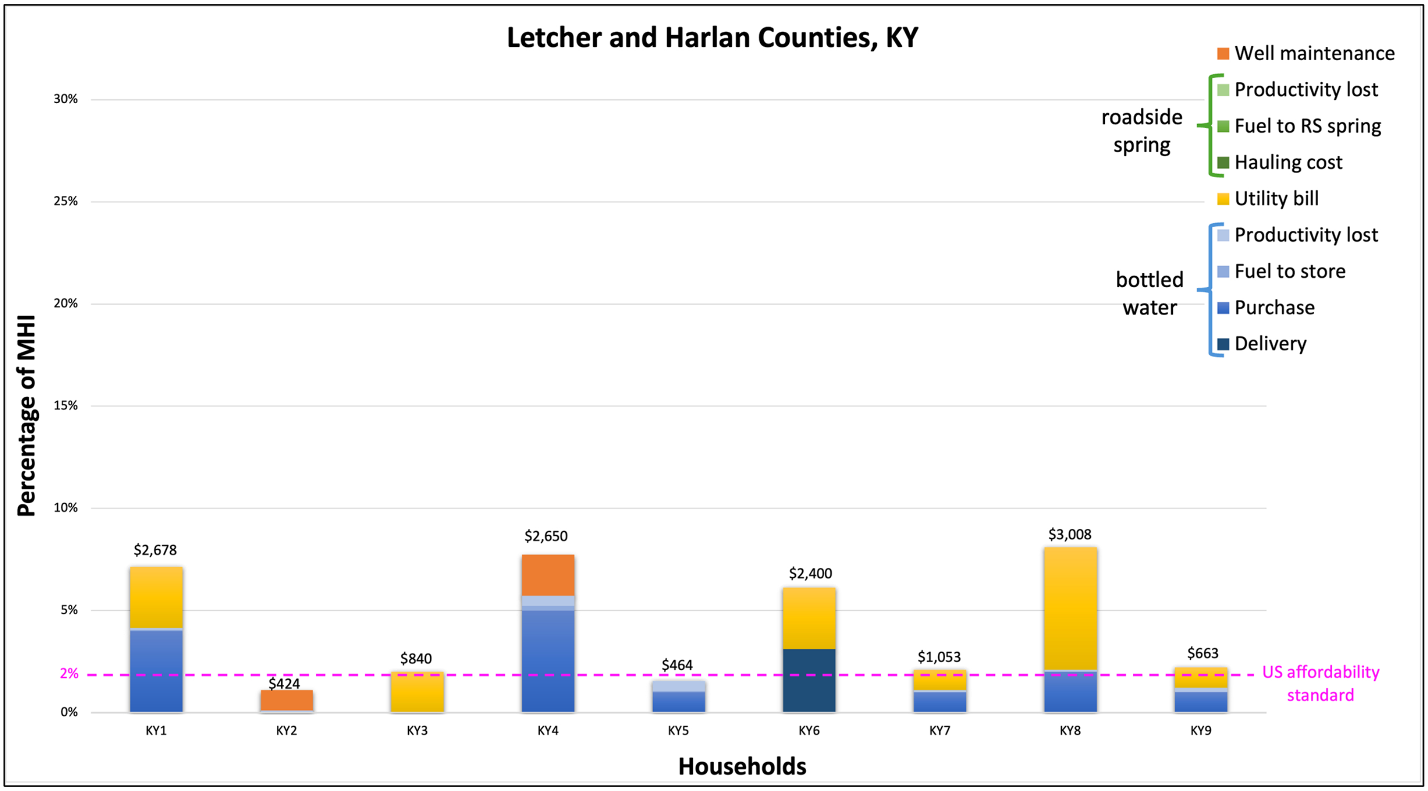

Fig 6. KY total expenditures. Letcher and Harlan Counties, Kentucky total water-related expenditures as a percentage of median county household income, ordered from lowest (left) to highest (right) reported household income. Total dollar amount spent by each household on water-related expenditures is presented at the top of each bar.

https://doi.org/10.1371/journal.pcsy.0000284.g006

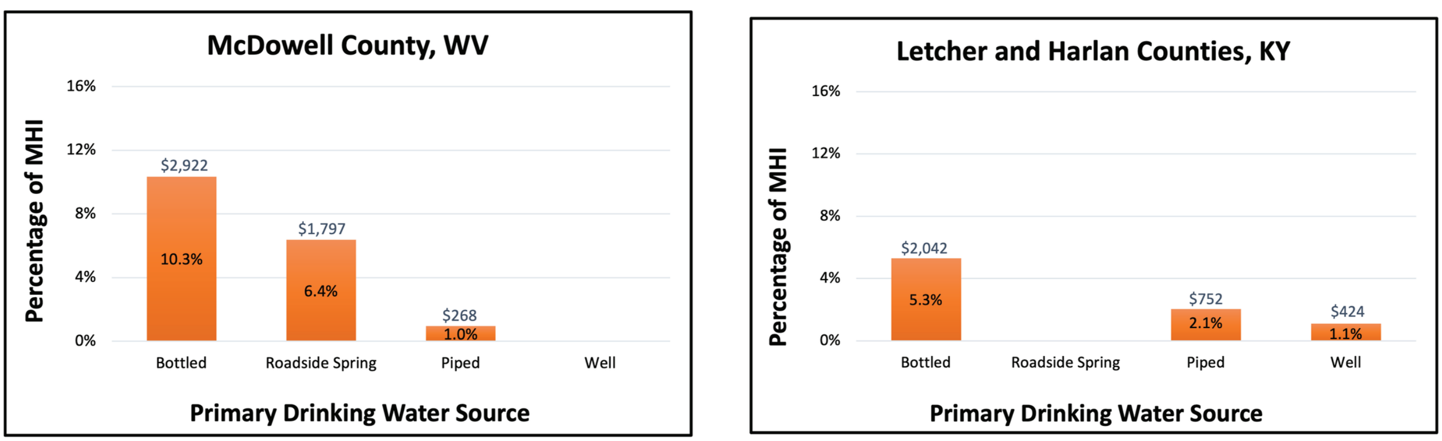

Fig 7. Average expenditures. McDowell County, West Virginia (left) and Letcher and Harlan Counties, Kentucky (right) average water-related expenditures as a percentage of median county household income by primary drinking water source.

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There is an inherent recruitment bias (i.e., self-selection bias as participating households are working with the community partners and may be experiencing severe water insecurity that is not representative of the community at large). Conversely, willingness to participate

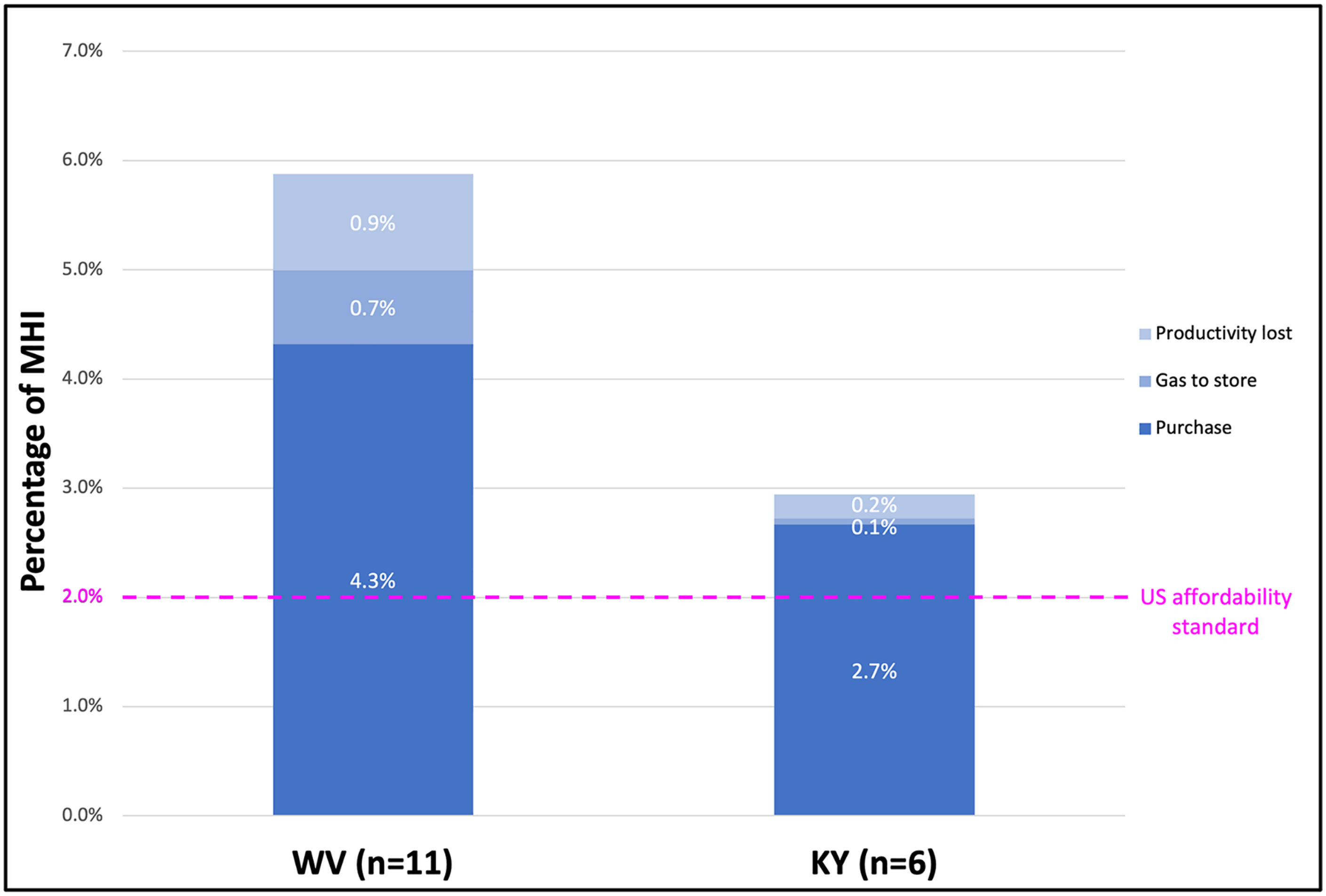

Fig 8. Average bottled water expenditures. Average bottled water expenditures as a percentage of MHI for households primarily reliant on bottled water for drinking.

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may also indicate that these households have the privilege or confidence to seek out external support to help with their water insecurity. In consideration of the recruitment bias and to maintain consistency with calculations of affordability as a percentage of median household income (MHI) from the United Nations Development Programme, World Bank, Organisation for Economic Co-operation and Development, and US Environmental Protection Agency [39,43,45,46], we compared the direct and indirect cost estimations to the MHI for the respective county, rather than the reported household income intervals. In McDowell County, WV, participating households had, on average, household income levels below the median county household income which led to our reported expenditures as a percentage of MHI being lower, on average, than the actual household expenditures experienced by participants. In Letcher and Harlan Counties, KY, participating households had, on average, higher household incomes than their respective median county household income which led to our reported expenditures as a percentage of MHI being higher, on average, than the actual household expenditures experienced by participating households.

This research begins to pave the way to considering a more holistic economic affordability approach to water expenditures. Additional indirect costs related to water insecurity that require attention include the costs of water treatment supplies (e.g., point-of-use filters), healthcare costs associated with water insecurity (e.g., medical bills from conditions associated with poor in-home water quality), additional productivity losses (e.g., taking a day off work to fix a well or missing a day of school due to water-related illness), and environmental impacts (e.g., plastic waste associated with bottled water use). Thus, our findings in this paper are likely still an underestimate of the true total economic burden faced by these households due to water insecurity.

However, despite the limitations, this study highlights major water affordability concerns in water-insecure Appalachian communities. The results also confirm the need previously expressed in the literature to consider direct and indirect costs to quantify the total economic burden of multiple-source water use on water-insecure households.

Conclusion

Though prior research in Appalachia has examined water quality metrics in line with United Nations Sustainable Development Goal 6, this study explicitly examined associated affordability. In keeping with previous national and regional studies, results suggest bottled water reliance is high in Central Appalachia and associated with perceptions of poor in-home water quality. Although the incidence of contamination in US bottled water appears low [28,62], which may make it palatable to communities with poor in-home quality, this effort highlights the high costs associated with bottled water acquisition. Reliance solely on bottled water to meet household potable needs inevitably exceeds proposed water affordability metrics, particularly in communities with high poverty.

The findings from this study suggest critical future avenues of research, investment, and design for policymakers concerned with drinking water access, affordability, and equity. By quantifying both direct and indirect economic expenditures associated with multiple-source water use, this research offers a more complete picture of the household-level impacts of water insecurity in rural communities, specifically in Central Appalachia. Results are of direct relevance to local and state public health departments, environmental protection agencies, rural water utilities, and agencies and nonprofits involved in infrastructure investment and affordability programs (e.g., USDA Rural Development, US Water Alliance). Quantitative analyses of the true costs of water insecurity are necessary to compare alternative water provision strategies, prioritize investments, and justify assistance programs. Improving in-home water access would likely result in freed income that could be invested in improving household education, health, and housing. At the community level, research suggests that there are economic returns of more than 5:1 for money invested into improving water access [24,58,63]. Ideally, quantification of economic burden will serve as motivation for the design of novel strategies and policy decisions aimed at improving water security and community well-being.

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