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Cash water expenditures are associated with household water insecurity, food insecurity, and perceived stress in study sites across 20 low- and middle-income countries

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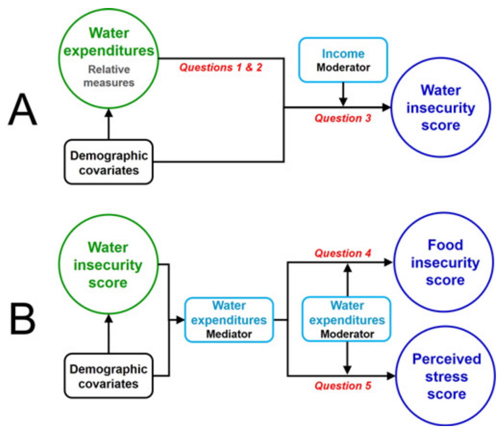
HIGHLIGHTS

- We assessed relationships between water expenditures, income, and water insecurity.
- Higher household water expenditures were associated with greater water insecurity.
- Higher water expenditures were associated with food insecurity and perceived stress.
- We observed no income threshold for households overcoming water insecurity.
- Water projects that increase household costs should be paired with anti-poverty measures.

GRAPHICAL ABSTRACT



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ABSTRACT

Billions of people globally, living with various degrees of water insecurity, obtain their household and drinking water from diverse sources that can absorb a disproportionate amount of a household's income. In theory, there are income and expenditure thresholds associated with effective mitigation of household water insecurity, but there is little empirical research about these mechanisms and thresholds in low- and middle-income settings. This study used data from 3655 households from 23 water-insecure sites in 20 countries to explore the relationship between cash water expenditures (measured as a *Z*-score, percent of income, and *Z*-score of percent of income) and a household water insecurity score, and whether income moderated that relationship. We also assessed whether water expenditures moderated the relationships between water insecurity and both food insecurity and perceived stress. Using tobit mixed effects regression models, we observed a positive association between multiple measures of water expenditures and a household water insecurity score, controlling for demographic characteristics and accounting for clustering within neighborhoods and study sites. The positive relationships between water expenditures and water insecurity persisted even when adjusted for income, while income was independently negatively associated with water insecurity. Water expenditures were also positively associated with food insecurity and perceived stress. These results underscore the complex relationships between water insecurity, food insecurity, and perceived stress and suggest that water infrastructure interventions that increase water costs to households without anti-poverty and income generation interventions will likely exacerbate experiences of household water insecurity, especially for the lowest-income households.

1. Introduction

Water affordability is critical for achieving global household water security. Since 2000, the Millennium Development Goals, and after 2015, the Sustainable Development Goals (SDGs), have guided the development of water and sanitation services in low- and middle-income settings. SDG Target 6.1 is “to achieve universal and equitable access to safe and affordable drinking water for all,” while 6.2 focuses on access to sanitation. The inclusion of the notion of ‘equity’ implies a concern with the enduring problem of differential water access by social or economic class. In other words, SDG Targets 6.1 and 6.2 can be interpreted as a call for water, sanitation, and hygiene (WASH) programs that recognize differential willingness and ability to expend cash resources for WASH services, though not at the expense of other services and goods such as food, housing, health, clothing, and education (United Nations General Assembly, 2015; WHO/UNICEF, 2017). This is in line with the SDGs' emphasis on a more holistic understanding of water accessibility and quality (Smiley, 2017).

Yet, the policy literature on WASH provision in low- and middle-income countries is strongly influenced by the notion that charging for water services is the best way to ensure that such services are appropriately allocated and financed (Anderson and Snyder, 1997; Grafton et al., 2011). Typically it is argued that charging more for water, on either a cost recovery or scarcity pricing basis, will remove inefficiencies built into existing models of public service provision and provide the necessary capital for maintenance and service expansion (Anderson and Snyder, 1997; Grafton et al., 2011). But there is mounting evidence that such approaches are not always associated with more comprehensive water services provision (Bakker, 2010; Bel and Warner, 2008; McDonald, 2014; Rusca and Schwartz, 2018; Staddon, 2010). Key challenges include the embedding of pro-poor cross-subsidies into the business model of private service providers, and the application of sufficiently robust regulatory oversight to ensure that social equity is not compromised—one might call these the *Cochabamba Challenges*. For example, in their 2017 World Bank report on African water services, Van den Berg and Danilenko (2017) note that few service providers have been able to successfully operate a pro-poor cross-subsidies-based model that does not risk other negative externalities.

Much of the world's poor acquire water from diverse sources, which are sometimes cost-free (e.g., natural surface waters) or communityowned (e.g., community kiosks or rainwater tanks), but are more commonly part of market-oriented water systems, whether operated by municipalities, private companies, or small-scale water entrepreneurs. People who are not connected to municipal water systems tend to pay the most for water (Allen and Bell, 2011, p.1). This general finding has been demonstrated in locations around the world, including India, Nepal, Kenya, and Colombia (Cook et al., 2016; Katuwal and Bohara, 2011; Zérah, 2000). These studies tend to find that, for poorer households, the cash element of water services costs can absorb up to 15% of total household cash income. These financial costs are well above international benchmarks for water affordability of 3–5% of household income/expenditure recommended by the World Bank, and 5% by the Asian Development Bank (ADB) (Fankhauser and Tepic, 2007). They also exclude the full range of opportunity costs and other sacrifices routinely made for water acquisition, such as foregone school and employment time for women and girls (e.g., Zérah, 2000), or capital maintenance of household or community systems (WHO/UNICEF, 2017). Many households lacking reliable access to clean water may have to buy water and invest in additional coping strategies, including buying household water storage containers, which increase household water expenditures (Coulibaly et al., 2014; Pattanayak et al., 2005). In India, Amit and Sasidharan (2019) found that as household income increased, the proportion of income spent on additional coping strategies decreased even while investments in pumping and high-volume water treatment increased. Based on these findings, an income threshold may exist that, once exceeded, allows households to implement coping strategies (e.g., additional storage or disinfection technology) that substantively reduce water insecurity.

The question is then: how can we meaningfully assess what that income threshold might be in a way that is relevant to understanding how it affects household well-being? Our assumption in this paper is that the household coping costs of meeting water expenditures can negatively affect households in many ways, as demonstrated for other necessities such as energy or food (Månsson et al., 2014; Russell et al., 2018). Drawing on literature from biocultural anthropology (Hadley and Crooks, 2012; Workman and Ureksoy, 2017; Wutich and Brewis, 2014), we use measures of reported water insecurity and two additional generalized markers of negative effects: perceived stress and reported household food insecurity. Both are considered to be tied intimately to human suffering, including suffering around water, albeit in slightly different ways. Perceived stress is an outcome measure used to understand how different situations affect our feelings and are appraised as stressful (Cohen et al., 1983), and has been associated with multiple forms of material poverty (Bisung and Elliott, 2017). Food insecurity is itself very stressful as a form of material poverty, both in terms of the actual threat of hunger and in terms of the meanings and feelings it evokes (Weaver and Hadley, 2009; Weaver and Trainer, 2017).

Water scholars have begun to recognize water insecurity's potential contribution to elevated reports of perceived stress (Bisung and Elliott, 2017). Research on perceived stress encompasses a range of assessments of social stress (e.g., evoked distress, perceived stress, symptoms of anxiety/depression). Water-related stress has also been shown to be associated with limited water access (Brewis et al., 2019a), experiences of water insecurity (Stevenson et al., 2016), shameful or conflictual water collection dynamics (Sultana, 2011), unpredictable and unjust water systems (Wutich and Ragsdale, 2008), and social inequality in water systems (Ennis-McMillan, 2001). As such, perceived stress measures can provide a valuable global summary assessment of the socioeconomic, cultural, and mental health toll of water insecurity.

More recently, food insecurity has emerged as an area of intensive focus in water insecurity scholarship, with efforts to better understand interconnections in the water-food nexus (Brewis et al., 2020; Wutich and Brewis, 2014). Water insecurity affects food insecurity through multiple pathways, including the lack of water for growing food, the inability to properly prepare cooked foods, and the high cost of buying water and food (Brewis et al., 2020; Collins et al., 2019). Food insecurity is thus a measure that helps capture the physical health effects of water insecurity, including those related to hunger and malnutrition. There is a substantial literature demonstrating that food insecurity is associated with higher levels of stress markers including depression and anxiety (Hadley and Patil, 2006; Tsai et al., 2012), perceived stress (Martin et al., 2016), and emotional expressions of distress (Pike and Patil, 2006). It may be that much of this is explained by food insecurity's association with water insecurity, but very few studies have explored this relationship (Brewis et al., 2020; Workman and Ureksoy, 2017; Wutich and Brewis, 2014).

This study leverages a data set managed by the Household Water Insecurity Experiences (HWISE) Research Coordination Network that was compiled in 2017 and 2018 from 29 sites in 24 low- and middle-income countries around the world (Young et al., 2019b). We use this unique comparative dataset to explore the complexities attending the relationship between household financial (i.e., cash) water expenditures and well-being, operationalized as a household experience-based water insecurity score. This analysis builds on the household water affordability literature by statistically testing whether higher household water expenditures are associated with water insecurity. In our first set of questions (Fig. 1A), we aimed to answer the following:

1. Are higher household water expenditures associated with a higher degree of water insecurity?
2. Is the relationship linear or is there a threshold beyond which the effect of higher water expenditures on water insecurity wanes or disappears entirely?
3. Does water insecurity decline at some level of income, regardless of expenditures, i.e., can a household financially "earn its way out" of water insecurity?

Next, we evaluated the relationship between household expenditures and indicators of well-being posited to be related to water insecurity, i.e. food insecurity and perceived stress, with two additional questions (Fig. 1B):

4. Do water expenditures mediate or moderate the association between water insecurity and food insecurity?
5. Do water expenditures mediate or moderate the association between water insecurity and perceived stress?

We report on our analyses of these research questions and discuss the implications for water pricing schemes, achieving SDG 6 water targets, and future water insecurity research. Our results advance understanding of the complex relationships between water insecurity, food insecurity, and perceived stress, with both empirical and theoretical implications for household water expenditures.

2. Methods

2.1. Sample

Our data are drawn from the Household Water Insecurity Experiences (HWISE) data set compiled in 2017 and 2018. The parent study involved over 7000 participants at 29 water-stressed sites in 24 countries (for details on each site's sampling strategy, see Young et al., 2019b). Study sites were located in sub-Saharan Africa, South America, Central America, the Middle East, Oceania, and Asia, each with a target sample of 250 households from urban, peri-urban, and rural settings. At all sites, informed consent was obtained prior to data collection by a trained enumerator with IRB oversight (from a variety of institutions). Consent and data collection were administered in the relevant local language. The survey was conducted with one eligible adult per household who self-identified as knowledgeable about the household's water situation. Not all households reported water

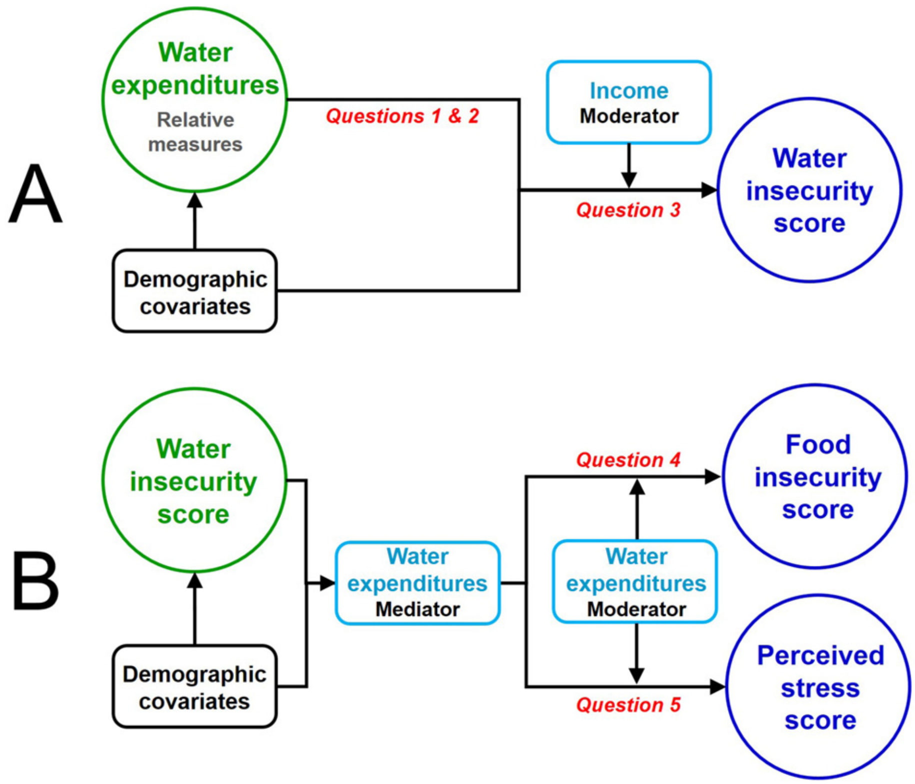

Fig. 1. Conceptual diagram of (A) research questions 1, 2, and 3, and (B) research questions 4 and 5.

expenditure data, and we excluded households from analysis if reported water expenditures were greater than three standard deviations from the respective site mean (i.e., unverifiable as either outliers or errors) and any other cases where key variables were missing. Because not all sites completed all modules, our final analysis included 3655 households from 23 sites in 20 countries (see Table 1).

Because this sample represents roughly half of all households in the HWISE data set, we analyzed select demographic differences between included cases and those excluded due to missing covariate data (see Supplementary Files, Table S1). In most cases, detected differences were attributable to the exclusion of entire sites such as Morogoro, Tanzania; Acatenango, Guatemala; and Upolu, Samoa. Though interpretation of our results is limited to water-insecure communities with profiles similar to our included sites, this is not unduly restrictive.

2.2. Water insecurity scores

Our water insecurity scores were constructed using items from the same water insecurity experiences module that was the basis for the HWISE Scale (Young et al., 2019a, 2019b). The cross-culturally validated HWISE Scale is composed of 12 items; 11 items were collected in all study sites, but the twelfth ("feelings of shame about the water situation") was only collected in the second sampling wave. In order to take advantage of data from all sites, we use an 11-item version of the scale that excludes the "shame" question. The 11-item water insecurity score accounts for 99.3% of the variation in HWISE Scale scores with minimal additional error.

The 11 items compiled into our water insecurity score queried the number of times in the prior four weeks that the household had experienced problems related to *water availability* (supply interrupted, no water availability at all), *quantity* (not enough to wash clothes, having to change foods eaten, not having as much to drink as liked, going to sleep thirsty), *hygiene* (inadequate water for bathing, inadequate water for handwashing), and *psychosocial dimensions* (worrying about having enough water, having one's day interrupted because of water problems, feeling upset/angry about the water situation). Likert-type responses were individually scored from 0 to 3 as: 0 = never, 1 = rarely (1–2 times in the previous four weeks), 2 = sometimes (3–10 times), 3 = often (11–20 times) or always (>20 times). We generated a score for each household by summing values across the 11 items, resulting in a range of 0–33, where higher scores indicate greater water insecurity.

2.3. Water expenditures and self-reported monthly income

We generated three relative measures of cash water expenditures (i.e., physical currency or electronic payments) using two survey questions that asked, "In the past 4 weeks, approximately how much money did you spend on getting water for your household?" and "What is the primary monthly income for your household?" First, we calculated expenditures as the site-specific *Z*-score of absolute monthly spending (in USD, converted at the time that data collection was completed at each site). Self-reported monthly income was also collected in local currency and converted to USD. Then, we calculated expenditures as the percent of monthly household income (in USD). Lastly, we generated site-specific *Z*-scores for the percent of income, yielding three currency-less measures of household water expenditures. We initially explored the unadjusted, absolute USD expenditures by site to understand the underlying variance in magnitude across sites. Because these values were not adjusted for purchasing power and are likely a proxy for the absolute differences in disposable income between lower- and middle-income nations, we do not analyze these any further.

We considered alternative measures of expenditures, such as standardization by purchasing power parity (PPP). But this was not possible because most study sites did not capture information about water volumes fetched or purchased, or unit costs for the many water sources used by participating households. Because local water pricing in water-stressed communities can be dynamic and is shaped by many factors such as weather, service outages, and politics (e.g., Bakker, 2003), PPP standardization is not more likely to offer stable short-term measures of water expenditures across sites, consistent with

Table 1
Study sites, number of households included in analyses, and mean and standard deviation (SD) of water expenditures expressed as absolute USD, and as a percent of monthly income, with Pearson's correlation coefficient (*r*) for each site's bivariate relationship between expenditures and water insecurity score.

Site	Country	Urbanicity	Primary drinking water sources (%)	Included households	Expenditures: absolute USD			Expenditures: % income		
					Mean	SD	*r*	Mean	SD	*r*
Africa										
Kahemba	Democratic Republic of the Congo	Rural	Surface water, 99.7 Other, 0.3	35	1.63	2.86	0.17	4.1	6.8	0.21
Bahir Dar	Ethiopia	Rural	Unprotected dug well, 25.1 Rainwater collection, 20.9 Standpipe, 13.5 Surface water, 13.5 Protected dug well, 12.4 Unprotected spring, 10.0 Other, 4.6	10	0.14	0.40	−0.12	0.1	0.4	−0.11
Accra	Ghana	Urban	Bagged/sachet water, 86.0 Borehole/tubewell, 5.7 Other, 8.3	142	8.05	8.38	0.09	11.4	13.4	0.15
Kisumu	Kenya	Rural	Surface water, 17.4 Borehole/tubewell, 16.2 Rainwater, 13.8 Piped water, 11.3 Standpipe, 10.9 Protected dug well, 10.1 Unprotected dug well, 7.7 Unprotected spring, 6.1 Other, 6.5	104	2.34	3.04	0.28***	7.8	13.6	0.17*
Lilongwe	Malawi	Peri-urban	Standpipe, 45.4 Piped water, 42.1 Other, 12.5	233	6.28	4.02	0.10	13.1	11.4	−0.05
Lagos	Nigeria	Urban	Bagged/sachet water, 48.9 Borehole/tubewell, 34.7 Other, 16.4	181	4.92	5.29	0.14*	6.8	9.1	−0.04
Singida	Tanzania	Rural	Standpipe, 48.6 Unprotected dug well, 17.4 Borehole/tubewell, 12.9 Other, 12.8 Unprotected spring, 8.3	457	0.78	1.15	0.10*	0.5	1.1	−0.00
Kampala	Uganda	Urban	Standpipe, 68.3 Other, 21.1 Unprotected dug well, 10.6	155	5.12	4.87	0.16*	6.8	7.3	0.14
Arua	Uganda	Rural	Protected dug well, 64.8 Unprotected spring, 19.6 Other, 15.6	178	0.22	0.23	−0.08	4.1	5.8	0.09
Asia										
Pune	India	Urban	Piped water, 89.4 Other, 10.6	142	0.26	1.20	0.42***	0.1	0.6	0.31***
Labuan Bajo	Indonesia	Urban	Bagged/sachet water, 36.9 Protected spring, 12.9 Piped water, 10.0 Tanker truck, 9.7 Standpipe, 9.3 Protected dug well, 6.5 Borehole/tubewell, 5.7 Other, 9.0	215	11.63	11.85	0.03	9.0	7.9	−0.01
Kathmandu	Nepal	Urban	Bottled water, 49.8 Piped water, 31.2 Tanker truck, 10.7 Other, 8.3	188	9.85	9.45	0.04	5.3	5.6	0.23***
Punjab	Pakistan	Peri-urban and rural	Standpipe, 26.6 Borehole/tubewell, 23.2 Piped water, 15.9 Rainwater collection, 14.2 Small water vendor, 10.3	39	20.50	14.01	−0.10	13.7	8.6	−0.24
Dushanbe	Tajikistan	Urban	Piped water, 58.2 Standpipe, 24.0 Tanker truck, 9.3 Other, 8.5	157	3.21	5.51	0.31***	3.6	6.9	0.30***
Latin America & Caribbean										
San Borja	Bolivia	Rural	Standpipe, 41.6 Tanker truck, 19.3 Other, 10.1 Borehole/tubewell, 8.0	14	15.41	14.90	0.14	8.6	8.1	0.29

(continued on next page)

Table 1 (*continued*)

Site	Country	Urbanicity	Primary drinking water sources (%)	Included households	Expenditures: absolute USD			Expenditures: % income		
					Mean	SD	*r*	Mean	SD	*r*
			Piped water, 7.6 Rainwater collection, 6.7 Bottled water, 6.7							
Honda	Colombia	Peri-urban	Piped water, 74.5 Standpipe, 20.4 Other, 5.1	129	9.51	5.47	0.04	8.1	10.2	0.06
Cartagena	Colombia	Urban	Piped water, 46.2 Standpipe, 34.6 Other, 12.4 Small water vendor, 6.8	138	5.27	6.28	0.24***	4.1	5.4	0.28***
Chiquimula	Guatemala	Rural	Piped water, 65.0 Unprotected spring, 15.3 Standpipe, 12.7 Other, 7.0	275	0.04	0.31	0.14*	0.0	0.3	0.14*
Gressier	Haiti	Peri-urban	Standpipe, 26.8 Small water vendor, 14.1 Bagged/sachet water, 13.1 Other, 10.9 Bottled water, 10.7 Borehole/tubewell, 9.3 Protected dug well, 7.9 Tanker truck, 7.2	105	0.54	1.58	0.02	2.2	5.9	−0.05
Mérida	Mexico	Urban	Bagged/sachet water, 50.0 Other, 33.6 Piped water, 14.4 Other, 2.0	199	6.61	6.26	0.18**	2.7	3.2	−0.07
Torreón	Mexico	Urban	Bottled water, 70.2 Piped water, 27.0 Other, 2.8	208	6.42	5.01	−0.03	2.5	2.7	0.09
Middle East										
Sistan & Balochistan	Iran	Urban, peri-urban, and rural	Small water vendor, 48.0 Other, 30.1 Piped water, 21.9	87	10.45	7.70	0.01	7.4	8.3	0.04
Beirut	Lebanon	Urban	Small water vendor, 54.5 Bottled water, 39.7 Other, 5.8	264	60.92	40.78	−0.13**	8.5	6.6	0.27***
Total				3655	8.60	19.44		5.2	8.0	

Note:
* = $P < 0.05$.
** = $P < 0.01$.
*** = $P < 0.001$.

ongoing debates about PPP among economists (Taylor and Taylor, 2004).

2.4. Food insecurity

The level of reported household food insecurity was collected using the 9-item Household Food Access Insecurity Scale (HFIAS) (Coates et al., 2007). The items in this index were phrased similarly to the water insecurity items, i.e. Likert-type responses with a 4-week recall period. Scores ranged from 0 to 27 with higher values indicating greater food insecurity.

2.5. Perceived stress

Perceived stress was collected in the survey using the short version of the Perceived Stress Scale (PSS) comprised of four items measured on a five-point Likert-type scale that are each scored from 0 to 4 (Cohen et al., 1983):

(1) "In the last month, how often have you felt that you were unable to control the important things in your life?"
(2) "In the last month, how often have you felt confident about your ability to handle your personal problems?"
(3) "In the last month, how often have you felt that things were going your way?"
(4) "In the last month, how often have you felt difficulties were piling up so high that you could not overcome them?"

PSS scores are obtained by reversing response scores (e.g., 0 = 4, 1 = 3, 2 = 2, 3 = 1 & 4 = 0) to the two positively stated items (items 2 and 3) and then summing across all four items (range 0–16) so that higher values indicate greater perceived stress.

2.6. Statistical analyses

We first examined the variation in each site's mean household water expenditures, and assessed the relationship between mean expenditures and a site's mean water insecurity score using Pearson's correlations. We then examined Spearman's rank correlations between each of our three measures of water expenditures and the frequency of selected survey items that were candidate covariates (e.g., a reported lack of money to buy water, and reports that water issues prevented households from earning money) to understand bivariate relationships (and potential collinearity) between the expenditure measures and covariates that may shape household water insecurity.

Although the site samples all employed random selection at the household level, several sites also first stratified by survey clusters (e.g., population strata, neighborhoods, or villages/towns). We fitted three-level tobit mixed-effects random intercept regression models using the metobit command in Stata v16.0 (College Station, TX), to account for clustering of participants within each site ($n = 23$), and survey clusters within sites ($n = 66$) as random effects. Tobit regression modifies the likelihood function to account for censoring of scaled dependent variables like our water insecurity, food insecurity, and perceived stress scores (Austin et al., 2000). We specified all lower limit censoring at zero and the upper limits to the maximum values for each score separately. All statistical analyses were performed in Stata and interpreted with a statistical significance threshold of $\alpha \leq 0.05$.

To answer question 1 about the relationship between water expenditures and water insecurity, we fit separate, multilevel tobit regression models using the water insecurity score as the dependent measure. Each model included one of our three independent expenditure variables of interest (absolute USD Z-score, % income, and % income Z-score) and a vector of level-1 fixed effects known to shape water insecurity or expenditures. These include the respondent's age and gender, as females often bear a disproportionate brunt of household water management (O'Reilly et al., 2009); the number of children in the household, which increases water demand (Arbués et al., 2003); whether the main drinking water supply was a vended source (e.g., tanker truck, bottled water, small vendor), which increases the unit cost of water (Katko, 1991); rural vs. non-rural geographic location, as rural areas generally suffer the largest gaps in water supply coverage (Cook et al., 2016); and the total amount of drinking and other household water stored in the household at the time of interview. The amounts of stored water help us indirectly control for seasonality and wealth effects, as water-stressed households store more water during drier weather and when they have the financial means to afford more or larger storage containers (Tucker et al., 2014). We hypothesized that higher expenditure levels of any kind would be associated with a higher water insecurity score.

To answer question 2, we evaluated the linearity assumption in this modeling technique using residual plots. Next, to evaluate question 3, we tested whether expenditures mediated the relationship between income and water insecurity by exploring how the presence and absence of the expenditures term affected the adjusted model coefficient for income. We then performed moderation analysis by including an interaction term between income and expenditures in the models with each of our three expenditure measures. In these interaction models, we hypothesized that households with the highest income and expenditures would be associated with lower water insecurity scores.

To answer questions 4 and 5 about water expenditures' respective relationships with food insecurity and perceived stress, we fitted separate sets of models using a similar specification described for question 1. We used the water insecurity score as an independent variable, and food insecurity or perceived stress scores as the outcomes of interest. In our mediation analysis, we first fitted adjusted models of food insecurity and perceived stress with the water insecurity score (our exposure of interest) and demographic covariates, and then separately introduced each of the three water expenditure measures to see if they substantively affected the adjusted model coefficient of the water insecurity score in magnitude or direction. In the moderation analysis, each set of three models of food insecurity and perceived stress included an interaction term between the water insecurity scores and expenditures (for each of the three expenditure measures), adjusted for demographic covariates.

3. Results

3.1. Descriptive statistics

Table 1 presents the sample sizes for each site along with the respective mean and standard deviations for absolute monthly water expenditures in USD, and for water expenditures expressed at a percent of monthly income. There was considerable variation in absolute monthly expenditures (mean = \$8.60, standard deviation [SD] = \$19.44) ranging from USD \$0.04 in Chiquimula, Guatemala, to USD \$60.92 in Beirut, Lebanon. The mean percent of income spent on water was 5.2% (SD = 8.0), just above international benchmarks for water affordability set by the World Bank and Asian Development Bank (Fankhauser and Tepic, 2007), and ranged from near-zero in Chiquimula, Guatemala, and 0.1% in Bahir Dar, Ethiopia, and Pune, India, to 13.7% in Punjab, Pakistan. We found similarly wide variation in the site-specific bivariate correlation coefficients between the two expenditure measures and the water insecurity score. Absolute USD water expenditures were significantly positively associated with the water insecurity score in nine sites with correlation coefficients ranging from 0.10–0.42 (Table 1). Only Beirut yielded a significant negative relationship (−0.13, $P = 0.004$).

Percent-of-income expenditures were significantly positively associated with water insecurity score in seven sites, with correlation coefficients ranging from 0.14–0.31 (Table 1). Beirut flipped from having water insecurity be negatively associated with expenditures to being positive (0.27, $P < 0.001$), and the correlations for several other sites changed in magnitude. There were no statistically significant negative associations. It is clear that the measure of expressing expenditures mattered, and that the unadjusted absolute USD measure may ultimately be a weak proxy for national income differences, with residents of middle-income nations generally able to spend relatively more on water in absolute terms than residents from lower-income nations. The remainder of our analyses use only the standardized water expenditures indicators.

3.2. Correlation analysis

Table 2 presents the Spearman's rank correlations among the three water expenditures measures and the frequency of households reporting "water problems prevented earning money," and "lacked money to purchase water." As expected, all of the water expenditure-related variables were significantly correlated with each other, with the highest correlation observed between absolute USD Z-score and percent of income Z-score ($rho = 0.65$, $P < 0.001$). The strongest correlation between any of these expenditure variables and *frequency of water problems preventing earning money* was for percent of monthly income spent on water ($rho = 0.25$, $P < 0.001$). The strongest correlation between the expenditure variables and *frequency of lacked money to purchase water*, was also observed for percent of monthly income spent on water ($rho = 0.32$, $P < 0.001$). These significant associations, while relatively weak compared with the expenditure measures themselves, demonstrate an initial statistically significant relationship between water expenditures and two fundamental aspects of water insecurity: interference with livelihoods, and financial barriers (Wutich et al., 2017).

3.3. Regression modeling: water insecurity

Our first set of regression models assessed whether household water expenditures were associated with water insecurity scores (question 1), and the linearity of any observed effects (question 2). We found consistent, positive associations between expenditures and water insecurity (Table 3, Models 1–3). Higher water expenditures were associated with higher water insecurity scores after adjusting for select household demographics and water storage practices, but with varying effect sizes for absolute USD Z-score ($\beta = 0.88$, standard error [SE] = 0.18, $P < 0.001$), % income ($\beta = 0.13$, SE = 0.02, $P < 0.001$), and % income Z-score ($\beta = 1.70$, SE = 0.18, $P < 0.001$). The expenditure measures based on Z-scores have larger coefficients because a 1-unit increase in Z-score is a much larger shift up the expenditure distribution curve than a 1 percentage point increase in percent-income. Therefore, the Z-score measure has a larger effect on the water insecurity score than the percent-income measure.

Table 2
Spearman's rank correlations (*rho*) between the three water expenditures measures, and the frequency of households reporting "water problems prevented earning money," and "lacked money to purchase water."

	Water expenditure measure			
	Absolute USD Z-score	% income	% income Z-score	Water problems prevented earning money[a]
Water expenditures measure				
Absolute USD Z-score	–			
% income	0.53***	–		
% income Z-score	0.65***	0.58***	–	
Characteristic				
Water problems prevented earning money[a]	0.10***	0.25***	0.11***	–
Lacked money to purchase water[a]	0.10***	0.32***	0.18***	0.50***

Note:
*** = $P < 0.001$.
[a] Higher values = more frequent.

Among the covariates, the number of children in the household ($0.27 \le \beta \le 0.29$, SE = 0.07, $P < 0.001$ in all models) and living in a rural context ($2.09 \le \beta \le 2.45$, SE = 0.71, $P < 0.003$ in all models) were significantly positively associated with a higher water insecurity score, while age was negatively associated with the water insecurity score and approached statistical significance ($\beta = -0.02$, SE = 0.01, $0.028 \le P \le 0.055$).

We then examined the residuals for the regression models of water insecurity scores in Table 3. The randomly dispersed, non-skewed pattern of the residuals, with few potential outliers, indicates that a linear fit was generally appropriate (see Supplemental Files, Fig. S1). Model 1 produced the most centered residual cloud and Model 2 produced a longer tail to the right, but the plots in Fig. S1 suggest homoscedasticity of residuals (i.e., that they are independent and identically distributed). In other words, there was no evidence of a threshold at which higher expenditures were associated with a lower water insecurity score.

For our mediation analysis, we added income to each of the three models of water insecurity scores in Table 3 and looked at the difference in the regression coefficient for income with, and without, each respective water expenditure measure in the model (question 3). There was virtually no difference, and thus no evidence that water expenditures mediated the relationship between income and water insecurity score, so we proceeded with the moderation analysis.

We assessed whether income moderated the relationship between water expenditures and water insecurity (also question 3) by adding an interaction term for income and expenditures to the models in Table 3. We observed statistically significantly positive associations between all water expenditure measures and the water insecurity score, again with stronger associations for the expenditure measures standardized as absolute USD Z-score ($\beta = 1.19$, SE = 0.20, $P < 0.001$) and percent income Z-score ($\beta = 1.36$, SE = 0.21, $P < 0.001$). We simultaneously observed consistently strong negative associations between income and the water insecurity score ($-3.46 \le \beta \le -2.35$, $0.39 \le \text{SE} \le 0.60$, $P < 0.001$ in all models). In other words, after adjusting for covariates, each additional $1000 of household income is associated with a water insecurity score that is 2.4–3.5 points lower, depending on how we define expenditures (Table 4, Models 4–6).

Table 3
Multilevel, mixed-effects tobit regression models of household water insecurity scores using three measures of household water expenditures and controlling for selected household characteristics ($n = 3655$).

	Model 1		Model 2		Model 3	
	β	SE	β	SE	β	SE
Fixed effects						
Water expenditures measure						
Absolute USD Z-score	0.88***	0.18	–	–	–	–
% income	–	–	0.13***	0.02	–	–
% income Z-score	–	–	–	–	1.70***	0.18
Household characteristic						
Age	−0.02	0.01	−0.02*	0.01	−0.02*	0.01
Gender	0.54	0.27	0.44	0.27	0.43	0.27
Number of children	0.29***	0.07	0.27***	0.07	0.28***	0.07
Amount of stored drinking water (in 100 s liters)	−0.00	0.00	−0.00	0.00	−0.00	0.00
Total water storage (in 100 s liters)	0.00	0.00	0.00	0.00	0.00	0.00
Primary water source is purchased/vended	−0.13	0.38	0.03	0.37	−0.06	0.37
Rural context	2.45**	0.71	2.16**	0.71	2.09**	0.71
Random effects						
Cluster	15.25	4.17	14.95	4.09	14.54	4.00
Site	29.68	12.44	26.74	11.49	30.23	12.42
Model diagnostics (log likelihood)	−9675.06		−9653.53		−9645.80	

Note:
* = $P < 0.05$.
** = $P < 0.01$.
*** = $P < 0.001$.

Table 4
Multilevel, mixed-effects tobit regression models of household water insecurity scores using three measures of household water expenditures and controlling for select household characteristics, including an interaction term for income and expenditure ($n = 3655$).

	Model 4		Model 5		Model 6	
	β	SE	β	SE	β	SE
Fixed effects						
Water expenditures measure						
Absolute USD Z-score	1.19***	0.20	–	–	–	–
% income	–	–	0.12***	0.02	–	–
% income Z-score	–	–	–	–	1.36***	0.21
Household characteristic						
Age	−0.02	0.01	−0.02*	0.01	−0.02*	0.01
Gender	0.52	0.27	0.41	0.27	0.42	0.27
Number of children	0.25***	0.07	0.26***	0.07	0.26***	0.07
Amount of stored drinking water (100 l)	−0.00	0.00	−0.00	0.00	−0.00	0.00
Total water storage (100 l)	0.00	0.00	0.00	0.00	0.00	0.00
Primary water source is purchased/vended	0.27	0.37	0.50	0.37	0.34	0.37
Rural context	2.27**	0.70	2.01**	0.70	1.99**	0.70
Income (USD 1000s)	−3.46***	0.41	−2.56***	0.39	−2.35***	0.60
Income ∗ expenditure (interaction term)	−0.23	0.34	−0.14	0.10	0.35	0.89
Random effects						
Cluster	14.14	3.90	14.37	3.94	14.04	3.87
Site	29.47	12.21	27.06	11.52	29.64	12.18
Model diagnostics (log likelihood)	−9625.43		−9621.98		−9618.81	

Note:
* = $P < 0.05$.
** = $P < 0.01$.
*** = $P < 0.001$.

The number of children in the household and rural context also remained statistically significantly positively associated with the water insecurity score in all models, and age was marginally negatively associated (Table 3). The interaction between water expenditures and income was not significant in any models, suggesting that income and water expenditures are independently associated with the water insecurity score. The interpretation of this interaction term is complicated because its frequency distribution is severely right-skewed; most surveyed households had very low income regardless of the water insecurity score. Households with high income and low water insecurity scores—despite being infrequent—can appear in the same part of the interaction term's frequency distribution as households with low income and high water insecurity, which is clearly a different household context.

Nevertheless, water expenditures and income were both strongly related to water insecurity with opposite effects, but independently so, and with varying strength depending on how one measures expenditures. Finally, the coefficients for the cluster and site random effects were consistently larger than those of any household-level fixed effects throughout Models 1–6, suggesting that location contributes substantially to the variation in water insecurity score, consistent with the bivariate results in Table 1.

3.4. Regression modeling: food insecurity

To explore whether water expenditures mediated or moderated the association between water insecurity and food insecurity (question 4), we fit separate models with each of our three expenditure measures using the Household Food Insecurity Access Scale (HFIAS) as the outcome of interest (Table 5). We began with our mediation analysis to test the differences in the regression coefficients for the water insecurity score with, and without, each respective expenditure measure in the model. There was no evidence that water expenditures mediated the relationship between water insecurity score and HFIAS score, so we proceeded with the moderation analysis.

Across all models, higher water insecurity scores were significantly positively associated with higher food insecurity scores; a 1-point increase in water insecurity was consistently associated with approximately a half-point increase in food insecurity. The percent-income ($\beta = 0.05$, SE $= 0.02$, $P = 0.017$) and percent-income Z-score ($\beta = 1.23$, SE $= 0.27$, $P < 0.001$) measures of water expenditures (Models 8 and 9) were significantly positively associated with food insecurity, again with the Z-score measure yielding greater magnitude. This is consistent with the positive relationships between expenditures and water insecurity, and water insecurity and food insecurity. Higher water expenditures expressed as the absolute USD Z-score were not associated with lower food insecurity ($\beta = -0.42$, SE $= 0.24$, $P = 0.078$).

The interaction term between water insecurity and expenditures was only significantly negatively associated with food insecurity for absolute USD Z-score (Model 7: $\beta = -0.05$, SE $= 0.02$, $P = 0.013$). Given the tiny effect sizes and the lack of any significant results for the interaction terms based on either of the percent-income-based expenditure measures, there was little evidence that expenditures moderated the relationship between water and food insecurity.

We found that age, number of children in the household, and rural context were significantly and positively associated with food insecurity across all models (with the exception that rural context only approaches significance in Model 7: $\beta = 1.23$, SE $= 0.64$, $P = 0.055$). Interestingly, using a primary water source that is purchased/vended was consistently, significantly associated with a lower food insecurity score ($-2.53 \leq \beta \leq -2.03$, SE $= 0.37$, $P < 0.001$ in all models), perhaps indicating some relationship between ability to pay for food and water respectively after adjusting for a household's degree of water insecurity, or perhaps being a proxy for income, i.e. households that can afford vended water can also afford food security.

Table 5
Multilevel, mixed-effects tobit regression models of food insecurity (HFIAS) scores using three measures of household water expenditures and controlling for select household characteristics, including an interaction term for water insecurity score and water expenditures ($n = 3655$).

	Model 7		Model 8		Model 9	
	Β	SE	β	SE	β	SE
Fixed effects						
Water expenditures measure						
Absolute USD Z-score	−0.42	0.24	–	–	–	–
% income	–	–	0.05*	0.02	–	–
% Income Z-score	–	–	–	–	1.23***	0.27
Household characteristic						
Age	0.02*	0.01	0.02*	0.01	0.02*	0.01
Gender	−0.26	0.26	−0.23	0.26	−0.23	0.26
Number of children	0.37***	0.07	0.34***	0.07	0.34***	0.07
Amount of stored drinking water (100 l)	−0.00	0.00	−0.00	0.00	−0.00	0.00
Total water storage (100 l)	−0.00	0.00	−0.00	0.00	−0.00	0.00
Primary water source is purchased/vended	−2.03***	0.37	−2.44***	0.37	−2.53***	0.37
Rural context	1.23	0.64	1.34**	0.64	1.31*	0.64
Water insecurity score	0.51***	0.02	0.49***	0.02	0.49***	0.02
Water insecurity score * expenditures (interaction term)	−0.05*	0.02	0.00	0.00	−0.04	0.02
Random effects						
Cluster	5.52	2.05	5.34	2.05	5.34	2.04
Site	16.68	6.49	16.57	6.46	16.56	6.47
Model diagnostics (log likelihood)	−8994.81		−9001.76		−8995.97	

Note:
* = $P < 0.05$.
** = $P < 0.01$.
*** = $P < 0.001$.

3.5. Regression modeling: perceived stress

We applied the same approach we used with food security to evaluate the relationship between water insecurity and perceived stress, using the PSS score as the outcome of interest (question 5). Again, we began with mediation analysis and explored the differences in the regression coefficient for the PSS score with, and without, each respective expenditure measure in the model. There was no evidence that water expenditures mediated the relationship between water insecurity score and PSS score, so we proceeded with the moderation analysis.

In all three models, higher water insecurity scores were significantly associated with higher PSS scores (Table 6, Models 10–12). Every measure of water expenditure was also significantly associated with perceived stress, although the directions of the relationships varied. Absolute USD Z-score (Model 10: $\beta = -0.19$, SE $= 0.09$, $P = 0.028$) was negatively associated with perceived stress, whereas percent-income (Model 11: $\beta = 0.02$, SE $= 0.01$, $P = 0.034$) and percent-income Z-score (Model 12: $\beta = 0.34$, SE $= 0.10$, $P = 0.001$) yielded positive associations. This may signal that perceived stress is tied to perceptions of water costs. Households may not associate a larger dollar amount of water costs, relative to their neighbors, as stressful alone. Rather, when these water costs are placed in the context of the overall household budget as a percentage, households are better able to contextualize relative water costs. The interaction term for water insecurity and expenditures was not significant in any of the models, indicating that these factors are independently associated with perceived stress. The associations between other household characteristics and perceived stress were relatively muted, compared with the earlier analyses of water and food insecurity, and generally non-significant with a few

Table 6
Multilevel, mixed-effects tobit regression models of perceived stress scale (PSS) scores using three measures of household water expenditures and controlling for select household characteristics, including an interaction term for water insecurity score and water ($n = 3655$).

	Model 10		Model 11		Model 12	
	β	SE	β	SE	β	SE
Fixed effects						
Water expenditures measure						
Absolute USD *Z*-score	−0.19*	0.09	–	–	–	–
% income	–	–	0.02*	0.01	–	–
% income *Z*-score	–	–	–	–	0.34**	0.10
Household characteristic						
Age	−0.00	0.00	−0.00	0.00	−0.00	0.00
Gender	0.14	0.10	0.15	0.10	0.15	0.10
Number of children	0.05*	0.03	0.04	0.03	0.04	0.03
Amount stored drinking water (100 l)	0.00	0.00	0.00	0.00	0.00	0.00
Total water storage (100 l)	0.00	0.00	0.00	0.00	0.00	0.00
Primary water source is purchased/vended	−0.25	0.14	−0.36**	0.14	−0.38**	0.14
Rural context	0.11	0.24	0.12	0.24	0.11	0.24
Water insecurity score	0.07***	0.01	0.06***	0.01	0.06***	0.01
Water insecurity score * expenditure (interaction term)	−0.00	0.01	0.00	0.00	−0.00	0.01
Random effects						
Cluster	0.70	0.22	0.64	0.21	0.64	0.21
Site	1.18	0.45	1.23	0.46	1.16	0.44
Model diagnostics (log likelihood)	−8567.39		−8562.57		−8561.48	

Note:
* = $P < 0.05$.
** = $P < 0.01$.
*** = $P < 0.001$.

relationships approaching the $\alpha < 0.05$ significance threshold. For example, the number of children was significantly positively associated with perceived stress in Model 10 using absolute USD *Z*-score ($\beta = 0.05$, SE = 0.03, $P = 0.047$), yet only approached statistical significance in Models 11 and 12 despite similar effect sizes. Likewise, having a primary water source that is purchased or vended was significantly associated with lower perceived stress in Model 11 using percent-income ($\beta = -0.36$, SE = 0.14, $P = 0.009$) and Model 12 using percent-income *Z*-score ($\beta = -0.38$, SE = 0.14, $P = 0.006$), yet was only marginally significant in Model 10. The coefficients for the cluster- and site-level random effects were also consistently smaller than those in the models of the water insecurity and food insecurity scores, indicating that geography may have less influence on perceived stress than for other constructs.

4. Discussion and conclusion

This study leveraged data from a larger parent study of water insecurity experiences in low- and middle-income countries to explore relationships between household water expenditures, water insecurity, food insecurity, and perceived stress. These data revealed a linear, positive association between relative measures of household water expenditures and a household water insecurity score, after adjusting for household demographic characteristics. For example, when measuring expenditures as percent of income, spending 10% more of the household's income on water was associated with a 1.2-point increase in the household water insecurity score after adjusting for household characteristics such as income, which drives the water insecurity score in the opposite direction. This is notable given the diverse drivers and experiences of household-level water insecurity.

The linear association between household water expenditures and our water insecurity score has important implications. It suggests that low-income households may face chronic water insecurity via tariff systems whose rate increases may exceed the rate of wage increases, and especially where communities are prone to water price shocks due to natural or human-triggered hazards. We recognize that cost recovery water pricing often attempts to build in cross-subsidies from higher- to lower-income domestic consumers. But price increases can nonetheless produce trickle-down price shocks in the decentralized and hybrid water supply systems used by many low-income households, especially when small-scale water providers, such as kiosk water venders, tanker services, or packaged water, are left to market forces (Amankwaa et al., 2014). We hypothesized that there might be some income threshold beyond which households are able to essentially earn their way out of water insecurity, and we observed no evidence of this—though there were very few households that exhibited both high income and high expenditures, and all the models suggest that any threshold might vary across nations and socio-economic contexts. Higher-earning households in our sample did, on average, experience improved water security relative to lower-earning households after adjusting for water expenditures; this provides additional support for calls for better integration of WASH and anti-poverty initiatives (Lombard et al., 2012), with the caveat that pro-poor pricing systems can present financial trade-offs for water companies (Ruijs, 2009).

Of note, there was no evidence of any interaction between expenditures and income, suggesting that water expenditures and income have independent effects on water insecurity. This is consistent with the many social mechanisms that can help higher-income households mitigate water insecurity without more direct spending on water services. For example, higher-income households often, on average, have access to different social networks and opportunities that may yield access to free water through professional employment settings, access to other "insider" water sources (legal or not), or higher value bartering relationships (i.e., having higher-order assets or services that can be used to secure water). Both high- and low-income households may also alleviate water insecurity by making investments with high upfront costs, such as paying for a piped connection, private well, or storage and disinfection resources which result in lower ongoing water expenditures. In some cases, pro-poor investment programs or development organizations bear the initial capital costs of such infrastructure in low-income communities.

Beyond water insecurity, our analysis also found that relative measures of household water expenditures were associated with greater food insecurity and perceived stress. These are relationships that we have not seen tested explicitly in prior studies. These findings provide further support to recent theoretical developments that position food insecurity and stress-related illness as core companion phenomena to household water insecurity (Brewis et al., 2019a; Brewis et al., 2020; Stevenson et al., 2012; Stevenson et al., 2016; Wutich and Brewis, 2014). Here, we briefly unpack each finding and its implications in greater detail.

Our data revealed a positive relationship between water insecurity and food insecurity, consistent with a recent study that used the same data but conceptualized water insecurity using a factor approach (Brewis et al., 2020). That study observed positive associations between water insecurity scores and HFIAS scores, with consistent positive associations between all sub-domains of water insecurity and food insecurity. These collective findings underscore the proposition that water insecurity is a driver of food insecurity—with water expenditures perhaps moderating this relationship—and suggest that a similarly integrated approach to mitigating water and food insecurity is required. Our mixed results in assessing water expenditures as a moderating factor are perhaps due to unknown income-related effects. Absolute expenditure measures were negatively associated with HFIAS scores—implying that certain expenditure levels could mitigate food insecurity, if not water insecurity—but relative measures using the percent of income spent on water were positively associated with HFIAS scores. Future studies with a more economically diverse household sample could help clarify these relationships.

Our data also revealed a positive relationship between water insecurity, water expenditures, and perceived stress, which corroborates prior findings about pathways between water insecurity and adverse mental health outcomes (Wutich and Ragsdale, 2008). Water insecurity and water expenditures were independently associated with perceived stress, suggesting different manifestations of cognitive load stemming from these phenomena. Future research on water worry and/or stigma could help elucidate the mechanisms by which social, biological, financial, and other dimensions of water insecurity produce stress and anxiety and possible moderating effects of gender and/or age in this relationship.

Our findings highlight the need for more careful measurement of water expenditures. Beyond the different measures used here to operationalize water expenditures, it is important to acknowledge that, in many low- and middle-income settings, households have long 'paid' for water in both cash and non-cash ways and there are often additional hidden costs of these water procurement strategies (Pattanayak et al., 2005). Such payments can be complex and multi-faceted, involving deployment of cash (to buy from a commercial vendor), time (to collect water from a distant source), and other forms of non-monetary exchange (e.g., reciprocity - Brewis et al., 2019b; Pearson et al., 2015; Stoler et al., 2019). These types of expenditures may be utilized simultaneously or cyclically for different types of water, depending on the context (Wutich et al., 2018), and all should be more rigorously measured in future studies. Because of the way our methodology resolved costs, we did not include non-monetary costs (e.g., time, foregone opportunities, etc.), nor do we account for water-related disability adjusted life-years, i.e. the loss in life-years due to water insecurity.

One common method for attempting to evaluate the value of non-market goods, the 'coping cost' approach, attempts to account for the multiple costs that can accrue as households pursue multiple tactics for securing household water. Such 'coping costs' can include goods or actions for which there are verifiable market prices (exchange of goods and services for cash as with tanker, bottled or sachet water purchase) and non-market prices estimated through methods such as 'revealed price' (Freeman III et al., 2014). But, as noted at the outset of this paper, it is difficult to monetize coping costs. For example, what is the value of lost children's labor or school time following diarrheal illness? One study, by Hutton et al. (2007) adopts rules of thumb about factors of GNI per capita, though notes the lack of a strong empirical basis. Monetizing the coping costs of stress would be even more formidable and would perhaps miss the point that not all dimensions of well-being are, or should be, monetized. This suggests avenues for future research that capture both the monetary costs of water for households (e.g., water expenditures) as well as the opportunity cost of obtaining water through non-cash means. In sum, the quantification of water expenditures impacts analytical results; this should be taken into account in future work on water costs and expenditures and water insecurity.

Our study findings must be interpreted with caution due to several limitations. This study used cross-sectional data from 23 culturally diverse study sites, known to struggle with water insecurity, in 20 countries that are broadly theorized to be representative of water-scarce communities around the world (Young et al., 2019b). We emphasize that the interpretation of our results is limited to water-insecure communities with socio-demographic profiles that resemble our included sites, with attention to sites' respective sample sizes used for analyses in this study. For example, other sites with high out-migration rates might yield different results if residents commonly earn their way out of water insecurity by moving to more water-secure neighborhoods. The data are also subject to seasonality bias (most sites were surveyed only once, sometimes in the wet season and sometimes in the dry season), and are not representative of any single country, thus limiting us from inferring any causal relationships between water expenditures, water insecurity, food insecurity, and perceived stress – mutually-reinforcing relationships that likely operate in both directions. The self-reported household water expenditure and income figures also may suffer from systematic inaccuracies, as has been shown with household estimates of water prices (Binet et al., 2014) and income (Moore et al., 2000). The variation in completeness of surveys across study sites also biases the results toward sites with a larger sample size, despite our efforts to control for this effect by using multilevel, mixed-effects regression modeling. Our modeling approach also focused on individual differences and did not include additional site- or cluster-level covariates, such as population and environment characteristics, that are theorized to shape water insecurity, food insecurity, or perceived stress. These types of processes could in turn interact with local household geographic patterns (e.g., income distributions), but our design did not assess local spatial effects.

Our analysis of the relationships between household water expenditures and water insecurity, food insecurity, and perceived stress suggests that—at best—only a small number of high-income households may be able to earn their way out of water insecurity, presumably by activating a wider range of coping strategies. These results also demonstrate that higher water expenditures are positively associated with food insecurity and perceived stress. One implication of this is that development programs focused on livelihood enhancement need to incorporate the costs of water services. Conversely, it can be concluded that water programs focused on using price to both finance and regulate service use may in some cases aggravate the problems they are trying to address. Subsidies may not be the answer either, as a recent World Bank report found that water subsidies, which tend to focus on networked services, disproportionately benefit high-income households (Andres et al., 2019). Achieving the SDGs, especially SDG 6.1 ("to achieve universal and equitable access to safe and affordable drinking water for all"), requires a paradigm shift that considers access as a multi-faceted dimension of water security, including relative water costs (Wutich et al., 2017).

Biophysical conceptualizations of water security are oriented around physical access to water. But the results of this study highlight the increasingly recognized importance of integrating social and economic factors (Cook and Bakker, 2012), such as having the financial means to pay for water services, once physical access via the requisite infrastructure is made possible. Global water security will also require involvement of water service providers to achieve a delicate balance in structuring tariffs for water services to cover the financial costs of providing services while also ensuring physical and financial access to these services for customers of all income levels.

Declaration of competing interests

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.

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Author contributions

JS and CS conceived the study and drafted the introduction and discussion. AP led data processing, statistical analyses and drafted the methods and results with JS. AW contributed significantly to the introduction and discussion. All authors contributed to the study design, read and edited the manuscript, and approved the final version.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.135881.

References

Allen, A., Bell, S., 2011. Glass half empty? Urban water poverty halfway through the decade of water for life. International Journal of Urban Sustainable Development 3, 1–7.
Amankwaa, E.F., Owusu, A.B., Owusu, G., Eshun, F., 2014. Accra's poverty trap: analysing water provision in urban Ghana. Journal of Social Science for Policy Implications 2, 69–89.
Amit, R.K., Sasidharan, S., 2019. Measuring affordability of access to clean water: a coping cost approach. Resources, Conservation & Recycling 141, 410–417.
Anderson, T., Snyder, P., 1997. Water Markets: Priming the Invisible Pump. Cato Institute, Washington, DC.
Andres, L.A., Thibert, M., Lombana Cordoba, C., Danilenko, A.V., Joseph, G., Borja-Vega, C., 2019. Doing More With Less: Smarter Subsidies for Water Supply and Sanitation. World Bank, Washington, DC.
Arbués, F., García-Valiñas, MaÁ, Martínez-Espiñeira, R., 2003. Estimation of residential water demand: a state-of-the-art review. J. Socio-Econ. 32, 81–102.
Austin, P.C., Escobar, M., Kopec, J.A., 2000. The use of the Tobit model for analyzing measures of health status. Qual. Life Res. 9, 901–910.
Bakker, K., 2003. Archipelagos and networks: urbanization and water privatization in the South. Geogr. J. 169, 328–341.
Bakker, K., 2010. Privatizing Water: Governance Failure and the World's Urban Water Crisis. Cornell University Press, Cornell, NY.
Bel, G., Warner, M., 2008. Does privatization of solid waste and water services reduce costs? A review of empirical studies. Resources, Conservation & Recycling 52, 1337–1348.
Binet, M.-E., Carlevaro, F., Paul, M., 2014. Estimation of residential water demand with imperfect price perception. Environ. Resour. Econ. 59, 561–581.
Bisung, E., Elliott, S.J., 2017. Psychosocial impacts of the lack of access to water and sanitation in low- and middle-income countries: a scoping review. J. Water Health 15, 17–30.
Brewis, A., Choudhary, N., Wutich, A., 2019a. Low water access as a gendered physiological stressor: blood pressure evidence from Nepal. Am. J. Hum. Biol. 31, e23234.
Brewis, A., Rosinger, A., Wutich, A., Adams, E., Cronk, L., Pearson, A., et al., 2019b. Water sharing, reciprocity, and need: a comparative study of inter-household water transfers in Sub-Saharan Africa. Economic Anthropology 6, 208–221.
Brewis, A., Workman, C., Wutich, A., Jepson, W., Young, S., 2020. HWISE-RCN. Household water insecurity is a plausible driver of food insecurity: evidence from 27 sites in low- and middle-income countries. Am. J. Hum. Biol. https://doi.org/10.1002/ajhb.23309 (forthcoming).
Coates, J., Swindale, A., Bilinsky, P., 2007. Household food insecurity access scale (HFIAS) for measurement of food access: indicator guide. Food and Nutrition Technical Assistance III Project (FANTA). FHI 360/FANTA, Washington, DC editor. version 3.
Cohen, S., Kamarck, T., Mermelstein, R., 1983. A global measure of perceived stress. J. Health Soc. Behav. 24, 385–396.
Collins, S.M., Mbullo Owuor, P., Miller, J.D., Boateng, G.O., Wekesa, P., Onono, M., et al., 2019. 'I know how stressful it is to lack water!' Exploring the lived experiences of household water insecurity among pregnant and postpartum women in western Kenya. Glob Public Health 14, 649–662.
Cook, C., Bakker, K., 2012. Water security: debating an emerging paradigm. Glob. Environ. Chang. 22, 94–102.
Cook, J., Kimuyu, P., Whittington, D., 2016. The costs of coping with poor water supply in rural Kenya. Water Resour. Res. 52, 841–859.
Coulibaly, L., Jakus, P.M., Keith, J.E., 2014. Modeling water demand when households have multiple sources of water. Water Resour. Res. 50, 6002–6014.
Ennis-McMillan, M.C., 2001. Suffering from water: social origins of bodily distress in a Mexican community. Med. Anthropol. Q. 15, 368–390.
Fankhauser, S., Tepic, S., 2007. Can poor consumers pay for energy and water? An affordability analysis for transition countries. Energy Policy 35, 1038–1049.
Freeman III, A.M., Herriges, J.A., Kling, C.L., 2014. The Measurement of Environmental and Resource Values: Theory and Methods. Routledge, Abington, UK.
Grafton, R.Q., Ward, M.B., To, H., Kompas, T., 2011. Determinants of residential water consumption: evidence and analysis from a 10-country household survey. Water Resour. Res. 47.
Hadley, C., Crooks, D.L., 2012. Coping and the biosocial consequences of food insecurity in the 21st century. Am. J. Phys. Anthropol. 149 (Suppl. 55), 72–94.
Hadley, C., Patil, C.L., 2006. Food insecurity in rural Tanzania is associated with maternal anxiety and depression. Am. J. Hum. Biol. 18, 359–368.
Hutton, G., Haller, L., Bartram, J., 2007. Global cost-benefit analysis of water supply and sanitation interventions. J. Water Health 5, 481–502.
Katko, T.S., 1991. Reselling and vending water. Journal - AWWA 83, 63–69.
Katuwal, H., Bohara, A.K., 2011. Coping with poor water supplies: empirical evidence from Kathmandu, Nepal. J. Water Health 9, 143–158.
Lombard, A., Kemp, M., Viljoen-Toet, N., Booyzen, M., 2012. An integrated developmental model for poverty reduction in South Africa: an NGO's perspective. J. Community Pract. 20, 178–195.
Månsson, A., Johansson, B., Nilsson, L.J., 2014. Assessing energy security: an overview of commonly used methodologies. Energy 73, 1–14.
Martin, M.S., Maddocks, E., Chen, Y., Gilman, S.E., Colman, I., 2016. Food insecurity and mental illness: disproportionate impacts in the context of perceived stress and social isolation. Public Health 132, 86–91.
McDonald, D., 2014. Rethinking Corporatization and Public Utilities in the Global South. Zed Books, London, UK.
Moore, J.C., Stinson, L.L., Welniak, E.J., 2000. Income measurement error in surveys: a review. J. Off. Stat. 16, 331–361.
O'Reilly, K., Halvorson, S., Sultana, F., Laurie, N., 2009. Introduction: global perspectives on gender–water geographies. Gender, Place & Culture 16, 381–385.
Pattanayak, S.K., Yang, J.-C., Whittington, D., Bal Kumar, K.C., 2005. Coping with unreliable public water supplies: averting expenditures by households in Kathmandu, Nepal. Water Resour. Res. 41.
Pearson, A.L., Mayer, J.D., Bradley, D.J., 2015. Coping with household water scarcity in the Savannah today: implications for health and climate change into the future. Earth Interact. 19, 1–14.
Pike, I.L., Patil, C.L., 2006. Understanding women's burdens: preliminary findings on psychosocial health among Datoga and Iraqw women of northern Tanzania. Cult. Med. Psychiatry 30, 299–330.
Ruijs, A., 2009. Welfare and distribution effects of water pricing policies. Environ. Resour. Econ. 43, 161–182.
Rusca, M., Schwartz, K., 2018. The paradox of cost recovery in heterogeneous municipal water supply systems: ensuring inclusiveness or exacerbating inequalities? Habitat International 73, 101–108.
Russell, J., Lechner, A., Hanich, Q., Delisle, A., Campbell, B., Charlton, K., 2018. Assessing food security using household consumption expenditure surveys (HCES): a scoping literature review. Public Health Nutr. 21, 2200–2210.
Smiley, S.L., 2017. Quality matters: incorporating water quality into water access monitoring in rural Malawi. Water Int. 42, 585–598.
Staddon, C., 2010. Managing Europe's, Water Resources: 21st Century Challenges. Ashgate Press, Surrey, UK.
Stevenson, E.G., Greene, L.E., Maes, K.C., Ambelu, A., Tesfaye, Y.A., Rheingans, R., et al., 2012. Water insecurity in 3 dimensions: an anthropological perspective on water and women's psychosocial distress in Ethiopia. Soc. Sci. Med. 75, 392–400.
Stevenson, E.G.J., Ambelu, A., Caruso, B.A., Tesfaye, Y., Freeman, M.C., 2016. Community water improvement, household water insecurity, and women's psychological distress: an intervention and control study in Ethiopia. PLoS One 11, e0153432.
Stoler, J., Brewis, A., Harris, L., Wutich, A., Pearson, A., Rosinger, A., et al., 2019. Household water sharing: a missing link in international health. Int. Health 11, 163–165.
Sultana, F., 2011. Suffering for water, suffering from water: emotional geographies of resource access, control and conflict. Geoforum 42, 163–172.
Taylor, A.M., Taylor, M.P., 2004. The purchasing power parity debate. J. Econ. Perspect. 18, 135–158.
Tsai, A.C., Bangsberg, D.R., Frongillo, E.A., Hunt, P.W., Muzoora, C., Martin, J.N., et al., 2012. Food insecurity, depression and the modifying role of social support among people living with HIV/AIDS in rural Uganda. Soc. Sci. Med. 74, 2012–2019.
Tucker, J., MacDonald, A., Coulter, L., Calow, R.C., 2014. Household water use, poverty and seasonality: wealth effects, labour constraints, and minimal consumption in Ethiopia. Water Resources and Rural Development 3, 27–47.
United Nations General Assembly, 2015. Report of the Special Rapporteur on the Human Right to Safe Drinking Water and Sanitation, A/HRC/30/39.
Van den Berg, C., Danilenko, A., 2017. Performance of Water Utilities in Africa. World Bank Group.
Weaver, L.J., Hadley, C., 2009. Moving beyond hunger and nutrition: a systematic review of the evidence linking food insecurity and mental health in developing countries. Ecol Food Nutr 48, 263–284.
Weaver, L.J., Trainer, S., 2017. Shame, blame, and status incongruity: health and stigma in rural Brazil and the urban United Arab Emirates. Cult. Med. Psychiatry 41, 319–340.
WHO/UNICEF, 2017. Safely Managed Drinking Water- Thematic Report on Drinking Water. World Health Organization, Geneva, Switzerland.
Workman, C.L., Ureksoy, H., 2017. Water insecurity in a syndemic context: understanding the psycho-emotional stress of water insecurity in Lesotho, Africa. Soc. Sci. Med. 179, 52–60.
Wutich, A., Brewis, A., 2014. Food, water, and scarcity: toward a broader anthropology of resource insecurity. Curr. Anthropol. 55, 444–468.
Wutich, A., Ragsdale, K., 2008. Water insecurity and emotional distress: coping with supply, access, and seasonal variability of water in a Bolivian squatter settlement. Soc. Sci. Med. 67, 2116–2125.
Wutich, A., Budds, J., Eichelberger, L., Geere, J., Harris, L.M., Horney, J.A., et al., 2017. Advancing methods for research on household water insecurity: studying entitlements

and capabilities, socio-cultural dynamics, and political processes, institutions and governance. Water Security 2, 1–10.
Wutich, A., Budds, J., Jepson, W., Harris, L.M., Adams, E., Brewis, A., et al., 2018. Household water sharing: a review of water gifts, exchanges, and transfers across cultures. Wiley Interdiscip. Rev. Water e1309.
Young, S., Boateng, G., Jamaluddine, Z., Miller, J., Frongillo, E., Neilands, T., et al., 2019a. The household water InSecurity experiences (HWISE) scale: development and validation of a household water insecurity measure for low- and middle-income countries. BMJ Glob. Health 4, e001750.
Young, S.L., Collins, S.M., Boateng, G.O., Neilands, T.B., Jamaluddine, Z., Miller, J.D., et al., 2019b. Development and validation protocol for an instrument to measure household water insecurity across cultures and ecologies: the household water InSecurity experiences (HWISE) scale. BMJ Open 9, e023558.
Zérah, M.H., 2000. Household strategies for coping with unreliable water supplies: the case of Delhi. Habitat International 24, 295–307.