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RESEARCH ARTICLE

Household water insecurity experiences and their perceived determinants in a low-income community of Cartagena, Colombia, during a water service expansion project

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Abstract

Traditional water indicators primarily focus on water quantity and quality, but emergent research demonstrates that measurement of lived experiences with water availability, accessibility, and use is important for understanding how household water insecurity impacts health and well-being. Few empirical studies have explored which household water insecurity experiences are most salient, or their potential causes, in Latin American cities. We analyzed data from 266 households in a low-income settlement of Cartagena, Colombia, to identify correlates and perceived determinants of water insecurity. The most prevalent household water insecurity experiences were water supply interruptions (96%), water worry (94%), and anger about the water situation (90%). Unexpected water interruptions and use of non-piped primary drinking water sources were associated with greater household water insecurity scores, water worry subscores, and hygiene subscores. Respondents perceived water issues in their community to be caused by deficiencies in gray infrastructure (49%), which included deficiencies in water distribution, treatment, or storage technologies. Social infrastructure (36%), including issues with political, economic, or administrative systems, was also cited as a barrier to water security. We did not detect significant relationships between water insecurity scores and the attribution of these problems to gray or social infrastructure, but there may be relationships between these factors and duration of residency and using a non-piped water source. These findings underscore the importance of socio-political factors and community engagement for improving urban water insecurity through slum-upgrade projects.

1 Introduction

Approximately 630 million people globally lack access to safely managed drinking water services and 1.7 billion people living in urban areas lack access to safely managed sanitation services [1, 2]. Climate change and infrastructure degradation are anticipated to increase the

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number of households experiencing issues with water availability, accessibility, and use (i.e., water insecurity) [3, 4], but traditional indicators of water, sanitation, and hygiene (WASH), such as water quantity (e.g., m3/capita) and quality, do not capture these important dimensions. Holistic indicators that consider the multiple components of water insecurity allow for a more comprehensive understanding of how water issues manifest at the household level and impact livelihoods [5, 6].

Previous studies using experiential scales have found that water insecurity is associated with poor physical health and mental well-being [e.g., 7–12]. Emergent literature demonstrates that water insecurity and mental health are linked through material deprivation and uncertainty, shame and social failure, worry about health threats, loss of connections to people and places, frustration around opportunity losses and restricted autonomy, interpersonal conflict and partner violence, and institutional injustice or unfairness [7, 13]. Indicators relating water insecurity to mental health could help practitioners identify WASH intervention strategies that may help to address depression, anxiety, and stress, and further justify the public health rationale for service coverage expansion. But few studies have applied these experiential water insecurity tools to communities in Latin America.

In Latin America, there are multi-faceted, and often overlapping, causes of water insecurity. Large-scale infrastructural and hydrological assessments are useful for identifying those factors that most acutely impact water availability and quality, including pipe breaks and political mismanagement. Individual perceptions about causes of water issues are also important for identifying drivers of water insecurity and tailoring interventions to the needs of local communities but are less commonly assessed. Programs and policies that address the priorities of individuals are likely to solicit greater community engagement and lead to greater project sustainability [14].

To develop a knowledge base for addressing water issues and mental distress in Latin America, we aimed to examine water insecurity experiences in the informal community of Villa Hermosa in Cartagena, Colombia. Using a mixed-methods approach, we sought to: (1) identify the most prevalent household water insecurity experiences, (2) assess whether water insecurity scores varied by household characteristics, (3) document perceived causes of local water issues, and (4) examine whether water insecurity experiences were associated with perceived causes of water problems. Findings from this study can be used by practitioners within the fields of water insecurity, water governance, urban development, and water service provision to inform sustainable urban development and streamline WASH and slum-upgrading policies.

2 Materials and methods

2.1 Ethics statement

This study was approved by the Institutional Review Board of Northwestern University (STU00204884) through an authorization agreement with the University of Miami. Participation was voluntary and explicit; verbal consent was requested and granted prior to conducting each survey. No personal identifiers were collected to ensure anonymity. Additional information regarding the ethical, cultural, and scientific considerations specific to inclusivity in global research is included in the S1 Text.

2.2 Study site and sample

Villa Hermosa is a low-income neighborhood in the south-west sector of Cartagena, Colombia, with approximately 5,600 residents living in 1,500–1,900 homes (see Fig 1). Villa Hermosa was founded in 2000 primarily by persons internally displaced from the country's violent civil conflict. At the time of data collection in 2018, housing in Villa Hermosa was not monitored

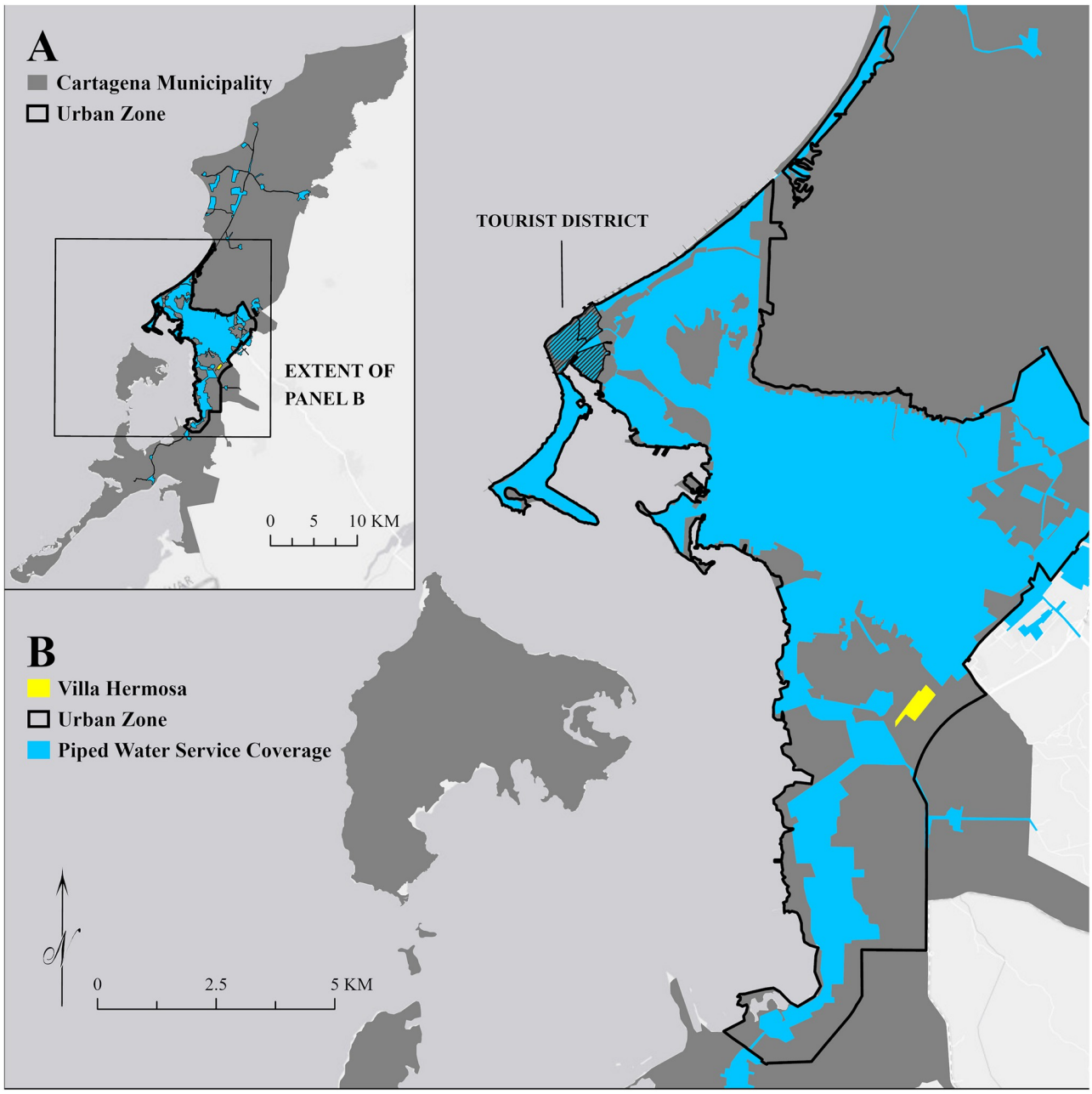

Fig 1. Piped water service coverage in Cartagena. Villa Hermosa, located in the urban zone of Cartagena, is situated outside the water service coverage area. Basemap source: Esri, HERE, Garmin, FAO, NOAA, USGS, OpenStreetMap contributors, and the GIS User Community: https://www.arcgis.com/home/item.html?id=291da5eab3a0412593b66d384379f89f.

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or regulated, residents lacked property tenure and access to basic services such as WASH, and roads were not paved–characteristics that are emblematic of informal and low-income communities globally [15–17]. The neighborhood exhibited high rates of crime and homicide, was susceptible to climate and environmental health stressors such as flooding and overflow of open sewage into homes, and is adjacent to an environmentally hazardous thermo-electric plant.

Villa Hermosa was selected as the study site both for its resemblance to informal, water-insecure communities in growing, mid-size cities, as well as its selection as the site of a state-sponsored WASH upgrading project. In 2016, a water and sanitation upgrade was proposed to provide household-level municipal water and sanitation services for each home in the neighborhood. At the time of data collection in 2018, the region's water and sanitation service provider, Aguas de Cartagena (Acuacar), was initiating the construction and installation of water and sewage infrastructure [18]. Prior to construction, Villa Hermosa's residents relied on alternative methods for water access, including water collection at community taps installed by Acuacar in 2008 and removed at the onset of construction. Community taps did not satisfy residents' needs due to intermittent and often unreliable service. Taps also created power struggles among community members over management, payment, proximity of homes to taps, and water pressure and contamination issues caused by illegal tampering with the pipeline serving the tap to create household-levels connections–colloquially called *artisanal* connections. Community-based services included pushcart rentals to transport water containers to tanker trucks and taps. Additionally, local businesses offered water delivery services via pushcarts, motorcycles, or donkeys, and refilled clients' water containers in their homes. Other forms of "alternative" water access in Villa Hermosa included tanker trucks sent by Acuacar, purchasing bottled and sachet water from private vendors, and household rainwater collection.

The study in Villa Hermosa was part of a larger umbrella project that aimed to develop a cross-culturally comparable tool for measuring household water insecurity, which ultimately led to the creation of the Household Water InSecurity Experiences (HWISE) scale [19]. Among 13 study sites throughout Latin America, sub-Saharan Africa, and Asia where the HWISE scale was first implemented, Villa Hermosa had the highest mean household water insecurity score [20].

The initial field visit to meet with community leaders in Villa Hermosa and receive permission to conduct research in the neighborhood took place in March 2018. In June 2018, we recruited survey enumerators from a local university. Enumerators were trained and briefed prior to data collection in July 2018. Training included a brief on research objectives, information about the study site and community, guidelines and ethics for engaging with study participants, sampling methods for identifying households, and tailoring of the survey instrument to respondents. Residents of Villa Hermosa were also recruited as guides for the enumerators to ensure the safety of enumerators and comfort of study participants.

Participants were selected using systematic random sampling within one of seven sectors (approximately 5 by 5 city blocks) of Villa Hermosa deemed safe by community guides. Within a sector, sampling was conducted by surveying every other available household along a given street. Participants were eligible for participation if they were at least 16 years of age (the age of consent in Colombia) and considered themselves knowledgeable about their household's water practices. All interviews were conducted in Spanish.

2.3 Data collection

Responses were initially recorded on paper surveys and then manually input into an electronic format. The survey questionnaire included questions about sociodemographic characteristics, primary water sources, and experiences with water issues. Participants were also asked to report what they perceived to be the primary causes of local water issues.

2.3.1 Primary outcome: Water insecurity. The HWISE scale consists of 12 items included in the original 32-item water insecurity module (see Table 1) [19]. For each item, individuals were asked to describe how frequently they experienced a particular water problem

Table 1. HWISE scale and subscore survey items included in the analysis. All items elicited the frequency of a given experience by beginning with the phrase, "In the past 4 weeks, how many times. . .".

Water Insecurity Items	HWISE scale	Worry subscore*	Hygiene subscore*
. . . have you or anyone in your household had to **change schedules/plans** due to problems with your water situation, such as problems getting or distributing water within the household? (Activities that may have been interrupted include caring for others, doing household chores, etc.)	X		
. . . has there not been **as much water to drink, as you would like**, for you or anyone in your household?	X		
. . . did you or anyone in your household **worry** you would not have enough water for all of your household needs?	X	X	
. . . have you or anyone in your household **been unable to wash hands** after **dirty activities** (e.g., defecating, cleaning animals, or changing a diaper) because of problems with water?	X		X
. . . has your household water supply from your main water source been **interrupted** or **limited** (e.g., water pressure, less water than expected)?	X		
. . . has there not been enough water in the household to **wash clothes**?	X		
. . . have you or anyone in your household had to **change what was being eaten** because there were problems with water (e.g., for washing foods, cooking, etc.)?	X		
. . . have you or anyone in your household gone to **sleep thirsty** because there wasn't any water to drink?	X		
. . . have there been **no usable or drinkable water** whatsoever in your household?	X		
. . . did you or anyone in your household feel **angry** about your water situation?	X	X	
. . . have you or anyone in your household had to go without **washing their body** because of problems with water (e.g., not enough water, dirty, unsafe)?	X		X
. . . have problems with water caused you or anyone in your household to **feel ashamed/excluded/stigmatized**?	X	X	
. . . have you or anyone in your household not washed the faces and hands of **children** because of problems with water?			X

* Jepson et al. [9] created two three-item subscores: worry subscore and hygiene subscore. Three worry items and two hygiene items are included in the HWISE scale.

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in the prior four weeks. These responses were scored from 0 to 3: 0 = "never"; 1 = "rarely" (1–2 times); 2 = "sometimes" (3–10 times); 3 = "often or always" (more than 11 times). These item scores were summed (range: 0–36), with higher scores indicating greater water insecurity. Worry and hygiene subscores were calculated based on Jepson et al. [9] (see Table 1). The water worry subscore includes three items: worry about the quantity of water for household needs, feeling angry about one's water situation, and feeling ashamed due to water problems. The hygiene subscore includes three items: inability to wash hands after dirty activities, inability to bathe or shower, and inability to wash faces or hands of children due to water problems. Higher subscores (range: 0–9) indicate greater experiences with worry over water or suboptimal water for hygiene. Although these subscores have not been cross-culturally validated, they are of theoretical interest for targeted water insecurity mitigation [9].

2.3.2 Covariates. Age, total people per household, and total years residing in Villa Hermosa were treated as continuous variables. All other items were treated as binary categorical variables: female (reference: male), displaced person status (reference: non-displaced person), unexpected water interruptions (reference: expected or announced interruptions), and non-piped sources primary source of drinking water (reference: piped primary water sources, i.e., artisanal household connections or community standpipe).

2.4 Data analysis

We first present descriptive statistics of respondent characteristics, experiences with household water insecurity, and hygiene and worry subscores (Objective 1). To identify water insecurity risk factors and account for nesting of responses within sectors of Villa Hermosa, we

developed a multilevel mixed-effects linear regression of HWISE scale scores (model 1) that controls for sector-level variation within Villa Hermosa. We also examined risk factors of water worry subscores (model 2) and hygiene subscores (model 3) using multilevel mixed-effects tobit models, which account for clustering of responses at the upper and lower extremes of the subscores. Each model included respondent characteristics (sex, age, total people per household, total years residing in Villa Hermosa, displaced status) and household water conditions (unexpected water interruptions, non-piped sources of drinking water) as potential risk factors (Objective 2). These variables were selected based on prior studies that examined correlates of water insecurity in other settings [2, 6, 7, 19, 21–23].

A similar analytic approach was used to identify factors associated with perceived causes of water problems. Responses to the open-ended question, "what do you see as the main cause of problems with water in your area?", were first divided into separate code segments to accommodate identification of multiple problems. Two of the authors (AKL, JDM) then categorized segments using *a priori* codes based on conceptualizations of "hard" and "soft" infrastructures [24], which were updated iteratively to include emergent themes. For analysis, we created two binary variables: one indicated whether gray infrastructure was identified as an issue and another to reflect whether social infrastructure was noted as a problem. Multilevel mixed-effects logistic regressions were used to assess whether water insecurity, controlling for other relevant covariates, were associated with odds of identifying gray (model 4) or social infrastructure (model 5) as a cause of water issues.

We performed sensitivity analyses to assess potential bias introduced from the selected covariates. Specifically, we ran every model without *type of water interruption* included, given that it was contingent on having experienced water interruptions. Results were similar in magnitude and direction of association when the variable was removed. As such, models with the full suite of identified potential risk factors are presented in the main text. Data were analyzed using Stata v17.

3 Results

3.1 Sample characteristics & HWISE scale scores

Most of the 266 participants were female (69%), married or in a civil union (67%), Christian (86%), and, on average, had lived in Villa Hermosa for 13 years (Table 2). About half (44%) of respondents self-identified as a displaced person. The average household size was five people (three adults and two children under 16 years), and monthly income per household was about US$202, below the World Bank's 2018 extreme monetary poverty line of US$3.20 per capita per day [25].

Most (71.3%) respondents rated their level of satisfaction with the local water situation as *not at all satisfied* while 4.2% were *completely satisfied*, the lowest and highest scale rankings, respectively. Among respondents who affirmed experiencing interruptions to the water supply, 78.5% reported interruptions that were not expected or announced (unpredictable water supply). 46.2% of participants used "artisanal" piped water, which was the colloquial name for an informal connection to the principal municipal provider pipeline feeding the community standpipe and usually consisted of suboptimal materials such as cracked tubes or hoses as pipelines. More than one-third (34.6%) of participants used community standpipes provided by Acuacar, and the remaining 19.2% of respondents used other non-piped sources including small water vendors, tanker trucks, bottled and sachet water, well water, and rainwater.

The mean HWISE scale score (n = 218) was 20.90 (SD = 7.50). Mean worry and hygiene subscores were 6.49 and 4.46, respectively. The most salient water insecurity experiences in

Table 2. Characteristics of adults participating in a study of local water issues in Cartagena, Colombia (n = 266).

Characteristics	Value (% or Mean ± SD)
Female	69.17%
Married (or in union)	68.32%
Christian	87.74%
Displaced	43.68%
Respondent age	40.75 ±15.10
Household composition	5.31 ±2.77
Adults per household	3.36 ±1.94
Children per household	1.95 ±1.54
Years in Villa Hermosa	12.76 ±5.48
Household income, USD[a]	201.98 ±108.72
Satisfaction with water situation	
Not at all satisfied	71.32%
Not satisfied	7.55%
Neutral	13.21%
Satisfied	3.77%
Completely satisfied	4.15%
Interruptions/predictability of water	
Expected interruptions	21.49%
Unexpected interruptions	78.51%
Primary source of drinking water	
Non-piped sources (e.g., vendors, tanker truck)	19.17%
Community standpipe	34.59%
Artisanal piped in home	46.24%
Water insecurity	
HWISE scale score	20.90 ±7.50
Worry subscore	6.49 ±2.32
Hygiene subscore	4.46 ±3.10

[a] Original responses were reported in Colombian pesos: 585,730.86 ±315,297.61 COP. In July 2018, the exchange rate was approximately 2,900 Colombian Pesos = 1 United States Dollar (USD).

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Villa Hermosa were *worry* about water (M = 2.49, SD = 0.88; 68.6% of respondents always *worried* that they would not have enough water for their needs), *anger* about the water situation (M = 2.45, SD = 0.99; 72.0% always felt *angry* about their water situation), and *interruptions* to the water supply (M = 2.45 SD = 0.80; 59.9% reported experiencing water *interruptions* more than 11 times in the previous four weeks) (Fig 2). The lowest rated items in the HWISE scale were also those with the highest proportion of respondents who reported never experiencing that item: going to *sleep thirsty* due to no water, *no water whatsoever* in the household, and inability to *wash hands* after dirty activities.

Other water insecurity experiences beyond those included in the HWISE scale were also salient in this context. Participants worried about the safety of the person getting water (M = 2.12, SD = 1.12): 52.4% of respondents experienced this *often/always*, and 23.2% experienced this *sometimes*. Less common experiences included difficulties with neighbors (M = 0.56, SD = 0.97), difficulties within the household (M = 0.50, SD = 0.92), and inability to tend to animals (M = 0.97, SD = 1.26) or crops (M = 0.84, SD = 1.17) due to problems with water.

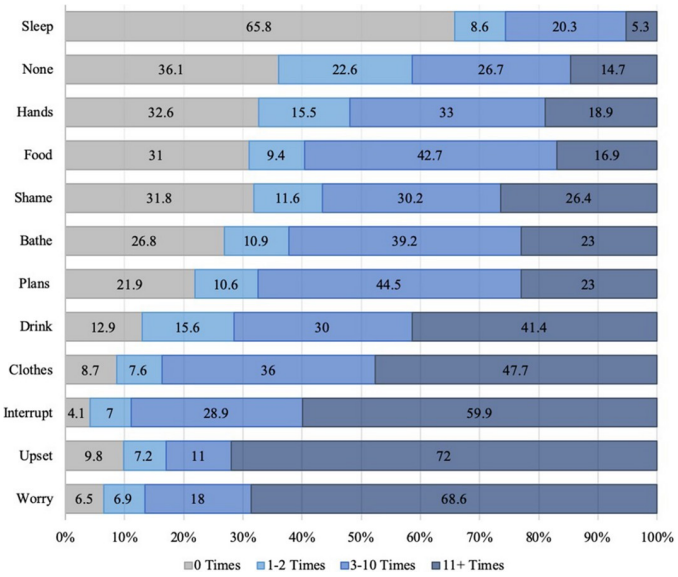

Fig 2. Frequencies of individual experiences included in the HWISE scale. Items are ordered by affirmation among participants in Villa Hermosa (n = 218). *Note*: figure adapted from Stoler et al. [20].

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3.2 Correlates of HWISE scale scores and subscores

Intraclass correlation coefficients suggested that 23.2%, 7.5%, and 7.8% of variation in HWISE scale scores, worry subscores, and hygiene subscores were due to between-sector differences. In multilevel mixed-effect models, unexpected water interruptions (relative to expected shut-offs) and use of non-piped water sources (relative to piped sources) were consistently associated with higher water insecurity scores (Table 3). For instance, experiencing unexpected interruptions (β = 3.95, SE = 1.07, $p < 0.001$) and use of non-piped water as the primary source

Table 3. Multilevel mixed-effects models of Household Water Insecurity Experiences (HWISE) scale scores, worry subscores, and hygiene subscores.

	Model 1: HWISE scale score (n = 197)	Model 2: Water worry subscore (n = 213)	Model 3: Hygiene subscore (n = 202)
	β (95% CI)	β (95% CI)	β (95% CI)
Total People in Household	0.10 (-0.19, 0.40)	0.06 (-0.06, 0.18)	-0.03 (-0.26, 0.21)
Female	1.38 (-0.49, 3.26)	0.47 (-0.31, 1.25)	0.81 (-0.60, 2.21)
Age	-0.02 (-0.08, 0.04)	-0.01 (-0.04, 0.01)	0.02 (-0.02, 0.07)
Years living in Villa Hermosa	0.11 (-0.04, 0.26)	-0.01 (-0.07, 0.05)	0.05 (-0.07, 0.16)
Displaced person (Ref: not displaced)	-0.30 (-2.02, 1.42)	-0.04 (-0.73, 0.66)	-0.22 (-1.53, 1.09)
Unexpected interruptions (Ref: expected interruptions)	3.95 (1.86, 6.05)***	1.63 (0.79, 2.47)***	1.70 (0.06, 3.33)*
Non-piped primary drinking water (Ref: community standpipe & household artisanal piped)	6.03, (3.69, 8.37)***	1.45 (0.46, 2.43)**	3.71 (1.91, 5.52)***
AIC	1276.35	874.26	913.41
BIC	1309.18	907.69	946.49

* $p < 0.05$;
** $p < 0.01$;
*** $p < 0.001$;
OR = odds ratio; CI = confidence interval.

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of drinking water (β = 6.03, SE = 1.19, $p < .001$) were associated with higher HWISE scale scores, relative to those experiencing no interruptions or using a piped water source, respectively (Table 3, model 1).

3.3 Perceived causes of water insecurity

Perceived causes of water issues ($n = 251$) were coded as resulting from gray infrastructure, green/blue infrastructure, social infrastructure, few sources, water quality, distance to source, none, unknown, unspecified, or other. Social infrastructure included political, social, economic, and administrative systems. Green/blue infrastructure included climatic or environmental conditions; gray infrastructure included water distribution, treatment, or storage technologies. We combined *water quality*, *distance to source*, and *unknown* under the *unspecified* category because responses within each of these categories did not explicitly attribute a specific infrastructure-related cause of water problems.

Fifty percent of respondents identified gray infrastructure as a cause of water problems (e.g., *broken pipes* or *low water pressure*) whereas 38.6% of respondents identified social infrastructure as a cause (e.g., *administrative corruption* or *no government recognition*). No respondents identified environmental or climatic factors as the primary cause of water issues. 14.7% of respondents identified an issue but did not explicitly identify the cause of the issue (e.g., *water quality* or *lack of water and services*).

In multilevel mixed-effects logistic regression models, water insecurity and relevant covariates were not statistically significant ($p < 0.05$) predictors of perceived cases of water problems (Table 4). Several estimates, however, reveal a probable association [26]. For example, in model 4, the 95% CI is mostly above the null, suggesting that use of non-piped primary drinking water is likely positively associated with identifying gray infrastructure as a primary cause of water issues ($p = 0.072$). Similarly, in model 5, the 95% CI suggests that years living in Villa Hermosa is likely positively associated with odds of identifying social infrastructure as a cause of water problems ($p = 0.078$).

4 Discussion

This study assessed the contributors and correlates of water insecurity experiences in the neighborhood of Villa Hermosa in Cartagena, Colombia using the HWISE questionnaire.

Table 4. Multilevel mixed-effects logistic regression of perceived causes of water problems.

	Model 4: gray infrastructure ($n = 191$) OR (95% CI)	Model 5: social infrastructure ($n = 191$) OR (95% CI)
HWISE scale score	1.00 (0.95, 1.05)	0.98 (0.94, 1.04)
Total People in Household	1.06 (0.95, 1.18)	1.00 (0.89, 1.11)
Female	1.18 (0.59, 2.35)	0.88 (0.43, 1.79)
Age	1.00 (0.98, 1.02)	0.99 (0.97, 1.01)
Years living in Villa Hermosa	0.96 (0.91, 1.02)	1.06 (0.99, 1.12)[†]
Displaced person (Ref: not displaced)	1.31 (0.72, 2.39)	0.60 (0.31, 1.16)
Unexpected interruptions (Ref: expected interruptions)	0.88 (0.41, 1.88)	1.05 (0.46, 2.41)
Non-piped primary drinking water (Ref: community standpipe & household artisanal piped)	2.34 (0.93, 5.92)[†]	0.55 (0.20, 1.52)

[†] $p < 0.10$;

HWISE = Household Water Insecurity Experiences; OR = odds ratio; CI = confidence interval.

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Among 13 low- and middle-income sites where the full HWISE scale was initially implemented [20], Cartagena had the highest mean water insecurity score (20.9). Cartagena's mean water worry and hygiene subscores (6.49 and 4.46), were also much higher compared to the respective subscores in Torreón, Mexico (2.45 and 0.97) [9]. The most prevalent household water insecurity experiences were related to psychosocial well-being and water supply interruptions. Unpredictability of these interruptions and use of non-piped primary drinking water sources were associated with higher water insecurity scores. Most residents perceived water issues to be caused by social or grey infrastructure. Our models suggested that there may be a relationship between duration of residence and attribution of water issues to social infrastructure, as well as between water source and attribution of issues to grey infrastructure, although there was meaningful uncertainty around these associations.

The most prevalent water insecurity experiences—and ultimately, the contributors to Villa Hermosa's rank as a highly water-insecure site—were related to psychosocial well-being. Worrying about not having enough water for all household needs, feeling angry about one's water situation, and experiencing interruptions to the water supply were frequently reported, with 78.5% of respondents reporting unexpected or unannounced interruptions. Each of these coincide with Wutich et al.'s [7] pathways through which water insecurity can drive mental ill-health, including material deprivation and uncertainty caused by unexpected water interruptions, highlighting the importance of and need to understand the social components (e.g., psychosocial, socio-political, socio-ecological) of water insecurity.

At the time of data collection, Villa Hermosa was undergoing the construction of a service upgrade to connect all households in the neighborhood to municipal public water and sewage services. Service upgrades, particularly in slums, are prone to difficulties that result in severe social disruption for community members [27], which may have exacerbated mental ill-health of respondents. Service upgrading difficulties in Villa Hermosa included frequent administrative and financial delays, disputes between community members and construction workers, political scandals and gang violence within the community, construction delays after rainfall due to flooding of roads, and engineering challenges in navigating the undocumented, informal piped network when installing new pipes (personal communication and observations, 2019). Ultimately, the construction process took longer than three years to complete (2018 to 2021), which may have exacerbated not only mental ill-health associated with water insecurity, but all water insecurity experiences, in addition to worsened conditions associated with the COVID-19 pandemic [28]. Thus, Villa Hermosa may also serve as an example of unintended consequences of slum upgrading and the need for municipalities to hold developers accountable for maintaining construction timelines and financial management—a topic in international development and slum upgrading that merits further attention.

Overall, the least frequently reported water insecurity experiences were about interpersonal difficulties within and outside the household (e.g., with family, neighbors, water vendors), and scenarios that included absolute scarcity (e.g., no water in the household, going to sleep thirsty, nowhere to purchase water). While these were the least affirmed items of the 32-original water insecurity items in Villa Hermosa, in-depth interviews with community members and other key stakeholders in the area revealed that arguments over water, corrupt leadership, and high gang activity and violence were prevalent (Lemaitre & Stoler, in review). Additionally, worry about the safety of the person fetching water was among the most affirmed items, although the survey instrument did not ask about specific safety hazards of concern. Crime is one of the barriers to WASH policy and construction in slums [16, 27], and interpersonal conflict is one of the pathways to mental ill-health associated with water insecurity [7]. Future studies may examine the relationship between different forms of safety and crime, mental health, and water security.

Our findings also demonstrate the importance of water source and predictability in determining water insecurity. Unexpected water interruptions and the use of non-piped water sources were similarly positively associated with water insecurity, worry subscores, and hygiene subscores across models. Non-piped water sources in low- and middle-income countries—including tanker truck delivery, stored water, vended water, and groundwater—are generally unsafe to drink, require greater time to access, and are potentially less predictable [29]. While the lack of piped water in the household has been well documented as a contributor to water insecurity, predictability of water source has been less studied. Unpredictability of water source or interruptions applies to both piped and non-piped water sources, including service interruptions, delivery timings or quantities, and natural events like drought. As shown in this study, unpredictable water interruptions were associated with water insecurity experiences overall and were positively associated with both water worry (mental health) and hygiene (physiological health). Unpredictability may lower trust in water providers and cause users to modify behaviors. A water insecurity study of Torreón, Mexico, observed similar results: unpredictability was associated with higher HWISE scale scores, even after controlling for intermittency [9]. Given robust literature that service intermittency is a human-driven factor, the relationships between unexpected or unannounced interruptions to the water supply and different forms of water insecurity merit further consideration in the context of infrastructure projects [30].

We did not find meaningful associations between water insecurity scores and perceived causes of local water issues (models 4 and 5). But the point estimates and associated confidence intervals suggested that, with a larger household sample or refined questions about perceived causes of water issues, factors such as water source and years residing in a community may be related to perceptions about the causes of local water. Such relationships could have implications for engaging long-term residents of communities during WASH expansion projects and prioritizing residents who depend on the least desirable water sources in order to improve popular support for infrastructure renewal, particularly when introducing new payment schemes.

The high sector-level variation of the HWISE scale scores in model 1 suggest that there may be a local "neighborhood effect" within Villa Hermosa. Households in some sectors may have had, on average, higher HWISE scale scores because of their distance from community taps or other water sources, lack of or damage to artisanal pipes, and the particular phase of construction and associated level of disruption at the time of data collection. Disruptions included damage to or removal of artisanal pipes, roadblocks or muddied roads that restricted mobility, and other daily inconveniences. Incorporating geospatial location data into survey collection to assess spatial components of water insecurity experiences could illuminate intra-community variation in these experiences. Such local variation in HWISE scale scores and similar subscores was demonstrated in rural Uganda [31].

Because data collection was conducted for the purpose of analyzing HWISE scale scores, the open-ended item about perceived causes of water problems was not of primary interest. Future studies can refine qualitative methodological approaches to better document individuals' lived experiences with water insecurity. In light of this limitation, we suggest future study designs include mixed-methods approaches to collect reliable and valid measures of sociopolitical and psychosocial factors as they relate to water insecurity, public services, and slum upgrading. Future studies should implement the HWISE scale to measure baseline water insecurity and understand causal effects of WASH upgrades on water insecurity in communities similar to Villa Hermosa [32, 33]. The findings of this study underscore opportunities for water utilities and WASH practitioners to improve service delivery by working with communities to develop contextually relevant measures, engage communities in the upgrade process, and use more holistic WASH indicators [34]. Broader WASH evaluation criteria can also help

to identify prevalent water insecurity burdens and help utilities to improve measurement of return on investment for WASH interventions [35].

This study was originally positioned to measure the intervention effects of the WASH upgrade project in Villa Hermosa using the HWISE scale and other water insecurity experiences. The second phase of data collection for this study was planned for 2021, contingent upon completion of the service upgrade construction, easing of COVID-19 travel restrictions, and the ability to ensure safety and minimize risk of spreading COVID-19 to survey enumerators and community members of Villa Hermosa. Ultimately, though, the follow-up wave of data collection was not possible due to the pandemic. Nevertheless, this study emphasizes the importance of implementing more robust WASH indicators, understanding user perceptions, and incorporating socio-political factors into WASH expansion projects, which may improve community engagement during these projects, expand the transformative impact of WASH interventions across multiple dimensions of well-being and quality of life, and improve the sustainability of WASH investments.

Supporting information

S1 Text. Inclusivity questionnaire.
(DOCX)

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