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A Structural Equation Model to Decipher Relationships among Water, Sanitation, and Health in *Colonias*-Type Unincorporated Communities

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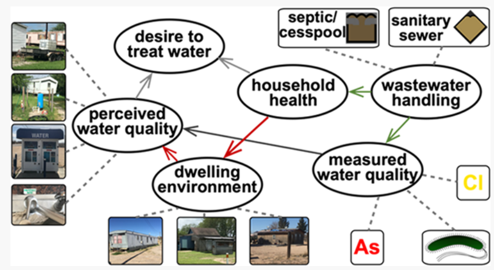
ABSTRACT: The *colonias* along the United States—Mexico border are generally self-built neighborhoods of low-income families that lack basic infrastructure. While some government assistance has provided roads and electricity, water and wastewater services are still lacking in many *colonias*. This research is the first to collect a comprehensive dataset on water, sanitation, health, and living conditions in these unincorporated neighborhoods through collection of water samples and surveys; 114 households in 23 *colonias* across three geographically diverse Texas counties are studied. Water quality is assessed via traditional microbial indicators, chlorine, and arsenic. This complex dataset requires an advanced statistical tool to disentangle relationships among diverse factors. Structural equation modeling is utilized to identify relationships among surveyed and measured variables. The model reveals that *colonias* residents with well/hauled water accurately predict their water quality, while those with treated+piped water tend to think that their water is worse than it actually is. Dwelling quality and connection to sanitary sewers influence perceived health risks and household health, respectively. Furthermore, these communities have an overwhelming need and desire for point-of-use water treatment. This model can inform decision making and may be adapted to probe other questions and social dynamics for water and sanitation in unincorporated communities elsewhere.



1. INTRODUCTION

Marginalized communities that lack a safe and reliable supply of drinking water not only exist throughout sub-Saharan Africa and Asia but also in developed countries.[1,2] Unfamiliar to many, *colonias* are generally unincorporated communities of low-income families in the United States (U.S.), primarily along the U.S.−Mexico border.[3] Many of the estimated 400 000 residents of Texas *colonias* rely on a water supply that is either inadequate or of questionable quality.[4,5] Those who are off-the-grid (i.e., lack access to centralized drinking water and wastewater treatment systems) either haul water or utilize household groundwater wells.[2] Many of these wells were built to meet immediate needs (i.e., not to code) and are shallow; they also can be contaminated by poor sanitation practices or by naturally occurring minerals like arsenic.[4,6,7] Public health concerns were evident in these communities in the 1990s, when cholera outbreaks were rampant in many *colonias*.[8] These episodic outbreaks prompted state regulations that imposed restrictions to such settlements.[8,9] The forced improvements to housing infrastructure have made an apparent enhancement in the living conditions.[5,10,11]

Housing conditions and improvements in one or several *colonias* located in a single county have been the focus of recent literature.[5,10,12,13] One such study for Starr County, Texas, documented household improvements over a ten-year period and found that many residents invested an average of $9,000 in their houses.[5] This finding demonstrates that *colonias* residents strongly desire to improve their living conditions. Despite these housing improvements, efforts have been insufficient, particularly with respect to the provision of safe and adequate drinking water. Such communities tend to have substandard septic systems, which correlate with gastrointestinal illnesses, respiratory problems, skin infections, and intestinal parasites.[6,14] These ailments also can be related to water availability, a known issue in the *colonias* due to their lack of infrastructure; this lack of access leads to packaged (i.e., pre-bottled or refilled) drinking water purchases.[15] For example, households (n = 71) in the *colonias* of Hidalgo County, Texas, reported spending an average of 7% of their income to purchase water from vending machines to refill water containers.[16] While water availability for the state-recognized *colonias* is reported in the database released from The Attorney

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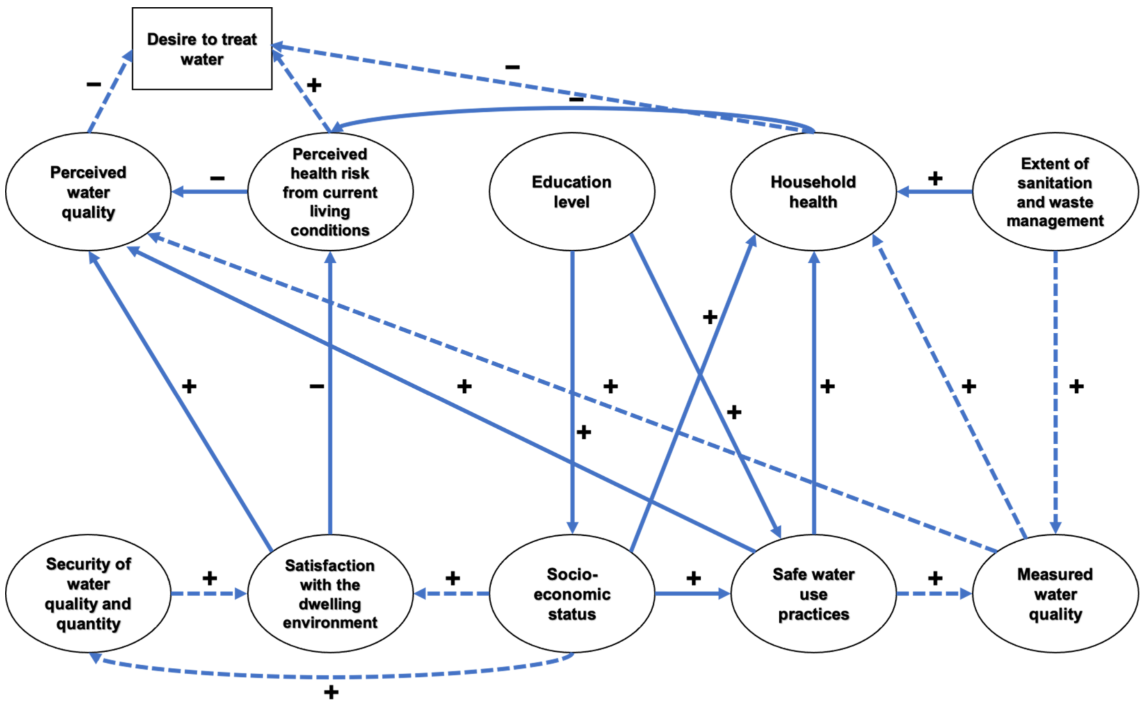

Figure 1. Conceptual structural equation model for the *colonias* showing the hypothesized relationships among variables relating to water, sanitation, health, and living conditions. Latent variables (i.e., measured by several surveyed variables) are shown in ovals, and the observed (i.e., directly measured) variable is shown in a rectangle. Solid lines represent relationships that have been used before in SEM,[28−34,37] and dashed lines are postulated. The independent variables have an arrow pointing away from them, and the dependent variables have arrows pointing toward them. Hypothesized positive and negative correlations are shown with a plus and a minus sign, respectively.

General of Texas,[17] reports of water quality and its effect on these communities are seldom documented.[4]

Several other studies on *colonias* have collected household surveys to explore relationships between social and infrastructural variables utilizing various statistical methods. One study used binary and ordered logistic regression models to examine how socioeconomic status might predict water insecurity (i.e., lacking adequate, reliable, and affordable water supply) in El Paso and Hidalgo Counties, Texas.[18] This study showed that immigration status was a stronger predictor of water insecurity than demographics, poverty, and housing infrastructure.[18] Another study, using chi-squared difference tests, observed no significant differences in water quality perception and management between *colonias* residents using well water versus hauled-stored water.[19] The *colonias* studies to date have used statistics to examine specific challenges that might not be representative of geographically diverse *colonias*. Widening the lens of the study to systematically probe more diverse social and environmental variables in these unique communities across Texas will facilitate future policy interventions on water infrastructure. Specifically, a comprehensive study that takes a holistic approach and quantitatively evaluates the relationships among water, sanitation, and health is necessary for these understudied communities. Such a comprehensive dataset necessitates the use of advanced statistical tools to reveal how diverse factors interact with each other.

Water and sanitation researchers have used numerous statistical tools to explore relationships and pathways of interaction.[20−24] Some of the most commonly used statistical methods, i.e., *t*-tests and linear mixed models, are ideal for the analysis of observed data (i.e., can be directly measured) and for probing direct effects between two variables (i.e., without mediation of another). However, disentangling relationships among diverse variables that can be directly or indirectly measured, like those needed to gain a comprehensive understanding of the *colonias*, requires a more advanced statistical tool. One such tool is structural equation modeling (SEM), which takes a confirmatory (i.e., hypothesis-testing) approach to the analysis of a structural theory bearing on some phenomenon.[25] This technique can incorporate both observed and latent variables from a holistic perspective, capable of simultaneous analysis of all of the hypothesized relationships. While latent variables cannot be directly observed, they can be inferred from other surveyed variables, e.g., perceived water quality cannot be accurately measured with one question. Perceived water quality is a multifaceted variable that not only captures the possible relationship between water quality and human health but also might include perception of its odor, clarity, and taste; thus, it is a latent variable that requires multiple questions for an accurate assessment.[26] Incorporating latent variables also allows the modeling of errors associated with observed variables, which is not possible in observed variable analyses. SEM thus not only provides distinct benefits over other statistical methods but can also posit itself within convergence research that brings together variables and measures from societal and scientific areas.[27]

A handful of researchers have utilized SEM to identify factors that impact perceived water quality,[28−34] while others have relied on summary statistics to analyze perception of sanitation and water quality in underserved communities.[26,35,36] The impacts of environmental health and household demographics on diarrheal health burden were explored with SEM in rural Guatemala and Brazil.[37,38] Specifically, this technique quantified the impact of higher education level, proper water filter maintenance, and improved water supply on

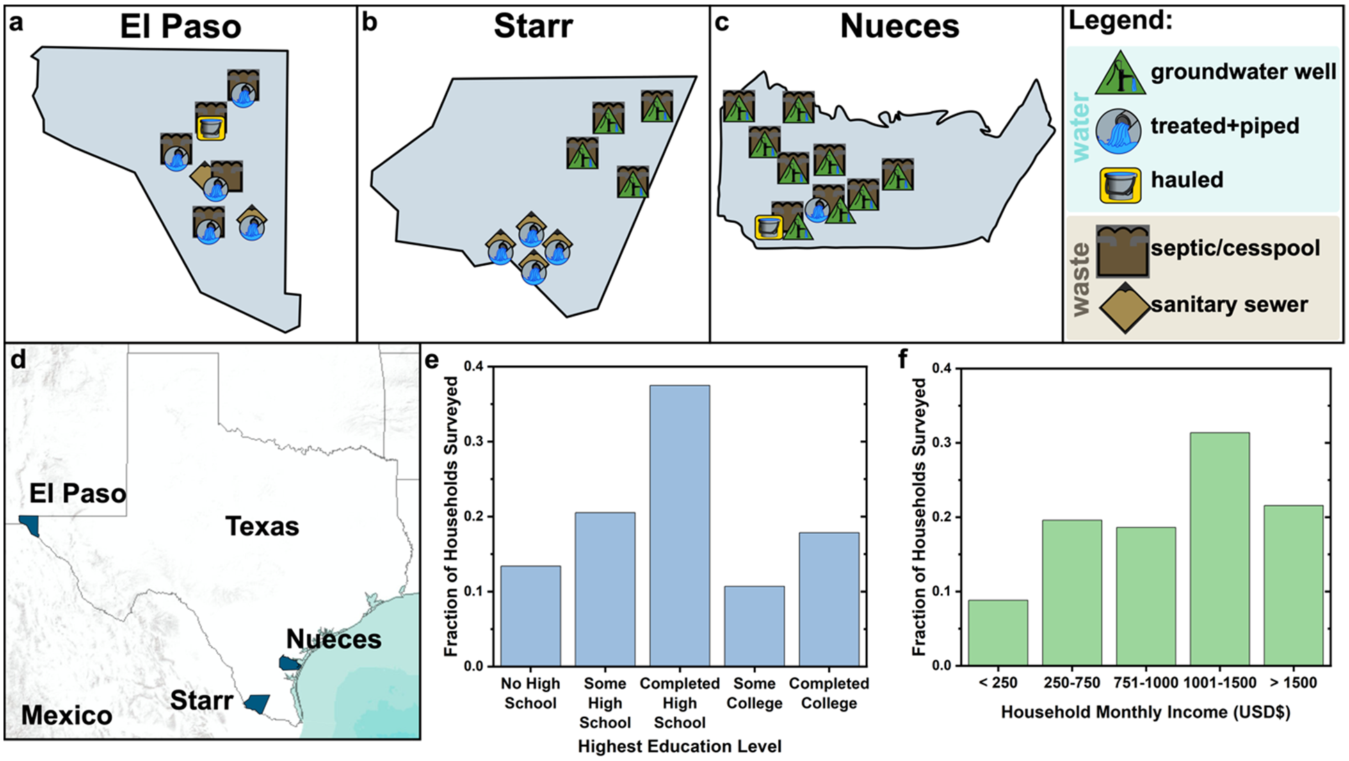

Figure 2. Geographical locations of the *colonias* by county; El Paso (a), Starr (b), and Nueces (c). The *colonias* are displayed with their respective methods for domestic wastewater handling and primary water sources. The location of each county is shown in the state of Texas (d). Socioeconomic status of surveyed *colonias* residents is shown by (e) education level and (f) household monthly income collected from the surveys during 2018 and 2019. Note that for the highest education level, "completed high school" included high school equivalency exams by GED.

reducing diarrheal health burden.[37] Another study used a comparative SEM technique (i.e., grouping different sample populations) to reveal that environmental exposure variables related to diarrhea and systemic inflammation proxies varied between female and male children under five.[39] However, no study has utilized SEM to assess the impact of measured water quality and extent of sanitation infrastructure on household factors (e.g., household health and perceived water quality) along with the need and desire for point-of-use (POU) water treatment. In the context of water and sanitation for unincorporated communities, SEM enables researchers to disentangle complex relationships among observed and latent variables. The ability of SEM to quantitatively describe pathways and its inferential nature of data analysis facilitate results that can directly decision making.

This study takes a holistic approach to develop a quantitative SEM framework to unlock relationships among water, sanitation, health, and living conditions for unincorporated communities (i.e., *colonias*). The objectives of this study were to identify drivers for water-use practices, assess the impacts of water quality, and report baseline household information for the *colonias* using a transferable statistical model. Data were collected through household surveys and water samples from 23 *colonias* across three Texas counties. Water samples were analyzed for microbial and chemical water quality, measuring a selected set of parameters. The goals of the baseline household survey were to gain knowledge of household water-use practices, document health and wellness information, and gauge the willingness to accept a water treatment technology. The relationships among these variables were quantitatively assessed using SEM. The results from this study can aid in the development of water treatment devices that meet technological requirements while being socially appropriate for the targeted communities. This study could enhance communication between research and policymaking to improve safe water access in these low-income *colonias* and beyond.

2. MATERIALS AND METHODS

2.1. Constructing the Structural Equation Model. The conceptual SEM, with hypothesized relationships between variables, is shown in Figure 1. The solid lines show the hypotheses informed by published SEM research,[28−34,37] whereas postulated hypotheses based on strong theory (not previously tested by SEM) are shown with dashed lines. One example of how these relationships can be read is as follows: *perceived water quality* is negatively influenced by *perceived health risks from one's current living conditions* and positively influenced by *measured water quality*, *safe water practices*, and *satisfaction with the dwelling environment*. A detailed description of SEM, the benefits of this modeling technique, and all tested hypotheses are in Supplemental Information (SI) Section SI.5. Details on the justification of these hypotheses and specific references are shown in Table SI.1.

2.2. Community Selection. This study focuses on three distinct counties in Texas (i.e., El Paso, Starr, and Nueces) (Figure 2). They are located in different geographical locations with unique climatic conditions. El Paso County is in a desert region, Starr County has a semiarid climate, and Nueces County is in a coastal area with a history of heavy rainfall. El Paso County includes the City of El Paso, which has its own water supply. The El Paso Water Authority is separate from Lower Valley Water District that supplies many of the *colonias* in the area with piped and trucked water. The majority of the

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colonias in Starr County fall into two groups. One group near the Texas−Mexico border is more developed, receiving piped water from Rio Grande City Water. The other group is in the north of the county and relies on household wells. Many of the Nueces County *colonias* use community or household wells. While some drinking water infrastructure has been installed in the area, many households in the Nueces County *colonias* cannot afford costly connection fees.[40]

The surveying and collection of water samples was conducted in each county with the goal of capturing some of the variation in available water infrastructure; in this effort, seven *colonias* in El Paso County, seven in Starr County, and nine in Nueces County were studied. The geographical locations of the *colonias* along with their respective domestic wastewater handling and primary water source(s) are shown in Figure 2.

2.3. Household Survey. A survey questionnaire was developed specifically for this research and modeled after previously developed questionnaires.[26,41−43] This survey aimed to gather information on water, sanitation, health, and living conditions. The survey was administered in either English or Spanish (Sections SI.1 and SI.2, respectively) to accommodate the language preferences of the surveyed household members. The survey design included probing the variables shown in Figure 1,[28−34,37] with latent variables comprised of at least three indicator questions or measures. The University of Texas Institutional Review Board approved the survey, which was administered to 114 households with 456 residents in total. The selection of households was completed by consulting with local partners to determine a central point in the *colonia*, from which bilingual researchers spread out and administered the paper surveys at randomly selected households.[26,44] The information from the survey was inputted into Microsoft Excel and double-checked to ensure accuracy.

2.4. Water Sampling and Testing. Water samples were collected from 85 of the 114 surveyed households. A detailed description of the water sampling and analysis is provided in Section SI.3. Water samples were not collected from every household; for example, when surveys were collected from two households that received water from the same public water supply source and were located in close proximately (e.g., neighboring), only one representative water sample was collected. The water samples collected from Nueces County were part of a study on the impact of rainfall on water quality and have been previously reported;[4] the water quality results collected during the wet period in the previous study were used herein because the surveys were collected at that time. The water quality from El Paso and Starr Counties has not been reported previously. Specifically, surveys and water samples were collected from El Paso County in January 2018, Nueces County in June 2018, and Starr County in September 2019. For statistical analysis, *measured water quality* was included in the model, either as *compliant* (given a value of 1 in the model) or *noncompliant* (given a value of 0 in the model) based on the following criteria. Using United States Environmental Protection Agency (USEPA) drinking water standards and maximum contaminant levels (MCLs),[45] water was deemed noncompliant if any of the following was observed: chlorine less than 0.2 mg/L for the treated water sample, arsenic greater than 10 μg/L, or presence of *Escherichia coli*. These parameters were selected as a baseline assessment of the health risks associated with household water and thus are not a comprehensive assessment of the water quality.

2.5. Structural Equation Modeling. One strength of SEM is that it can incorporate both observed and latent variables. To incorporate latent variables into the model, an analysis needs to be completed to assess if measures or questions accurately describe the variation in (or "load" onto) the latent variable. Confirmatory factor analysis (CFA) was utilized to assess these loadings. The software package M*plus* was used with "by" statements to load observed variables (code in Section SI.5). Significant loadings (p-value < 0.05) with a magnitude of 0.4 or greater were used to calculate individual factor scores for each latent variable when at least three loadings met this criterion. The factor scores, determined for each household, allowed for a parsimonious model and decreased model run time. These factor scores were combined with the observed variables for each household and used for the SEM. All of the pathways in the conceptual model were simultaneously solved using M*plus*. The output from this model yielded standardized direct effects, each with a corresponding p-value. Indirect pathways were tested by bias-corrected bootstrapping with 10 000 replications.

One latent variable of particular interest to this study is the household's *perception of water quality*. In the survey, five questions were asked to probe *perception of water quality* and were scored based on a Likert scale (1 strongly disagree and 5 strongly agree). Three of the questions were found to be significant (Table SI.2). The numerical grades to these questions were summed for the overall perception of water quality. The following criteria were used: poor (3−6), fair (7−11), and good (12−15).[26]

3. RESULTS AND DISCUSSION

3.1. Sociodemographic Status of the *colonias* Residents. Three questions in the survey were asked to assess *education level* (Table SI.2) and were loaded onto a single factor. While the *percentages of people in the house that speak and write in English* met the necessary standardized loading (i.e., 0.4), the *highest education level of anyone currently living in the house* did not. Therefore, this factor was dropped from the SEM because it did not accurately describe the variation within the surveyed households. The older generation in many of the households is "Spanish-speaking only", while the younger generation, enrolled in grade school, is usually bilingual. This language disparity, along with low education level, could be the cause of the factors not loading onto the latent variable of education level. It is notable that the older Mexican−American generation in this region experienced extralegal discriminatory practices with regard to their educational experience.[46] Overall, in 34% of the households surveyed, the *highest education level of anyone currently living in the house* is less than a high school degree (Figure 2e).

Six questions in the survey were asked to assess *socio-economic status* (Table SI.2). The household monthly incomes are shown in Figure 2f. Among all of the households surveyed, 47% have a monthly income <$1,000. As a reference, the U.S. Department of Health and Human Services sets the poverty line at $1,063.33/month for households of one person and $2,183.33 for households with four people.[47] According to this metric, many of the surveyed households live below the poverty guidelines. Some of the higher-income households are skilled laborers, such as construction workers, mechanics, truck drivers, or plumbers. Of the six questions loaded onto a single factor designed to probe *socioeconomic status*, only two of the surveyed variables met the necessary criteria. Socioeconomic

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Table 1. Water-Use Practices Shown by the Water Source Used for Drinking and Other Uses With Mean Household Cost[a]

1. Percent of households using the water source for drinking
2. Percent of households using the water source for other uses
3. Mean household cost ($/month)

	primary water sources			secondary water sources	
County	treated + piped	well	hauled	vending water	bottled water
El Paso	18%	0.0%	3.0%	39%	82%
	82%	0.0%	0.0%	0.0%	1.5%
	$57.50	$0.00	$45.00	$10.60	$23.10
Starr	8.8%	0.0%	0.0%	38%	65%
	77%	24%	0.0%	0.0%	0.0%
	$54.50	$0.00	$0.00	$10.00	$34.60
Nueces	14%	29%	0.0%	43%	86%
	14%	86%	7%	0.0%	0.0%
	$52.50	$62.50[b]	$60.00	$13.20	$30.00
Total	16%	4.3%	2.6%	40%	77%
	72%	18%	1.7%	0.9%	1.7%
	$56.60	$62.50[b]	$52.50	$11.10	$27.20

[a]Note that some households utilize multiple sources for drinking and other uses, so all percentages do not add up to 100%. [b]The cost associated with this well water is from the *colonia* of Cyndie Park, which utilizes a community well and charges households a flat rate of $62.50 per month. All other wells belong to individual households with no monthly fees.

status can be challenging to assess in a community that is low to medium income, with a high level of homogeneity (e.g., poor distribution of measures).[18] *Socioeconomic status* was not used in the SEM developed here due to the existing similarity; however, future studies should consider the inclusion of this parameter.

3.2. Source of and Expenditure for Drinking Water. Table 1 shows the primary and secondary water sources of the surveyed *colonias*. Overall, a majority of the households surveyed utilize treated + piped water and wells as their primary water source. Many of the *colonias* surveyed in El Paso County have access to treated + piped water and spend, on average, $56.47/month on it. However, only 18.2% of households in this county utilize this source for drinking. The Zaragosa *colonia* in El Paso County was the only one surveyed that did not have access to piped water, relying strictly on hauled water; those households spent an average of $45/month on water. The primary water source in Starr County depends on geographical location. The *colonias* near the Texas−Mexico border have access to treated+piped water, whereas the more rural ones in the northern part of the county utilize household wells. Only 8.8% of households in Starr County drink treated+piped water, even though 76.5% of the households are within this distribution network. The majority of Nueces County *colonias* have household wells, but only 28.6% of the population drink their well water. While some of the surveyed *colonias* in Nueces County do have access to piped water, only a small fraction (14.2%) of households surveyed were actually connected to this supply due to high connection fees. In general, the majority of the households in these *colonias* do not utilize their primary source of water for drinking.

Most of the surveyed households utilize bottled water (77.4%) and vending-machine refills (40.0%) for drinking. The monthly expenditure for bottled water ($27.24) is higher than that for vending-machine water ($11.07). These vending machines tap into existing piped water supplies and provide additional treatment for their water; for instance, the national company Watermill Express advertises that their systems utilize ion exchange, filtration, reverse osmosis, and ozonation/ultraviolet disinfection.[48] These machines are found in or near more populated urban areas and are popular as they provide an affordable and reliable supply of potable water. However, some rural *colonias* do not have access to nearby vending machines, so their residents must rely on bottled water. One study in Hidalgo County (just east of Starr County in southern Texas) found that *colonias* residents tend to depend on these vending machines even as improvements in water infrastructure provide treated+piped water to their homes.[16] The practice of utilizing refillable water containers (i.e., *garrafones*) is also common in Mexico.[26] Both of these studies on the *colonias* and communities in Mexico report that households spend a significant portion of their income on refilling these water containers, despite having access to an affordable treated + piped supply of water.[16,26] The use of water containers might be due to a lack of trust in the quality of the treated+piped water.

To further probe the choice of drinking water source, the households that purchase water from another source for drinking (i.e., bottled or vending-machine water) were prompted with four choices (of why). The choices (and the

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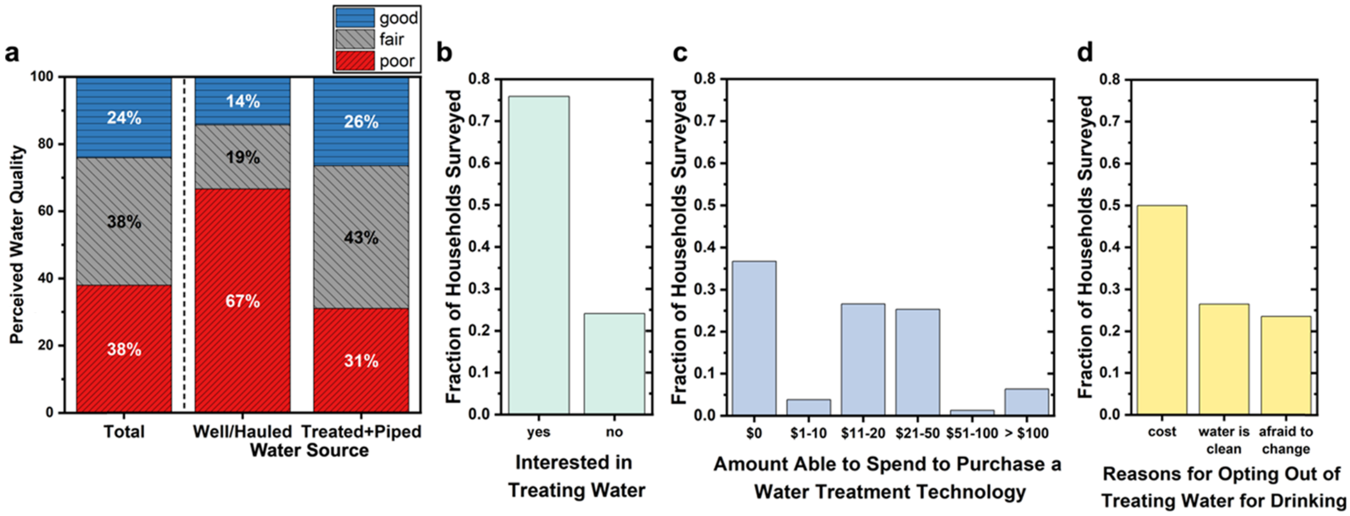

Figure 3. (a) Perceived water quality reflected in the surveys for all of the *colonias* and grouped based on primary water sources. Desire to treat water shown by (b) interest in treating water at the POU, (c) amount able to spend to purchase a water treatment technology, and (d) reasons for opting out of treating water for drinking. Note that sizing how much the community members are able to spend reflects currency denominations in U.S. dollar bills (i.e., $10, $20, $50, $100). These increments can help to assess which POU treatment technology might be more affordable and appropriate. Some affordable options include ceramic pot filters ($7−$30) and slow-sand filters ($12−$17), whereas a more expensive option might be a membrane-based system (>$100).[49]

percent of respondents indicating each choice) include the following: *you were told the tap water (well or piped) is unsafe* (22.8%), *it is your belief to buy separate drinking water* (32.4%), *you have always drunk purchased water only* (24.6%), and *other* (14.9%). The most common *other* reason related to the poor taste of the tap water. These results are aligned with the notion that purchasing water from a separate source is likely embedded in their cultural practice, as demonstrated by residents' the most common answers (57%): *belief to purchase* and *always have purchased.*

Five survey questions assessed *security of water quality and quantity* (Table SI.3). Two of these surveyed variables, both pertaining to water quantity, met the necessary criteria for factor loading. Both of these questions pertain to water quantity. The households seem to have a plentiful supply of water, but the quality is thought to be unreliable. Therefore, grouping *security of water quality and quantity* into a single factor does not load well and was not used in the SEM.

3.3. *Colonias* Residents' Perception of the Quality of Their Water. The *perception of water quality* was probed with five questions. Three of these surveyed variables met the necessary criteria and were included in the analysis (Table SI.2). The measures that did not load were *perception of color* and *odor of the water*, which were used in an earlier study and also were nonsignificant there.[26] These measures were included here as a check for bias during the survey and were not used for future analyses. The calculated factor scores for *perceived water quality* were used in the SEM.

When looking at the *perception of water quality* for all of the *colonias* surveyed (i.e., total), a fairly even distribution of perceived water quality was observed (Figure 3a). When examining the impact of the grouping based on the primary water source, distinct differences were observed. For households relying on well or hauled water, 67% believed their water to be of poor quality and 33% believed it to be fair to good. On the other hand, 69% of the households with treated+piped water believed their water to be of fair to good quality, and only 31% believed it to be poor. The results of the grouping of *perceived water quality* based on county are shown in Figure SI.4, where the differences can be attributed to the primary water source. The *measured water quality* was used to determine risks associated with the primary water source, and SEM was utilized to probe if the surveyed households were accurate predictors of their water quality.

3.4. Residents' Willingness to Adopt a Treatment Solution and Barrier(s) to Such Intervention. POU water treatment technologies could provide an immediate opportunity for these households to improve their water quality. Several questions in the survey were asked to assess the participants' *interest in treating water* and *amount that they are able to spend on a water treatment device* (Figure 3b,c). When asked if they would be interested in treating their water treatment before drinking, 75.9% of households answered *yes*, though 36.7% of those interested said they could not afford to spend any amount of money on water treatment devices. Only 6.3% of the households said they could afford to spend over $100. The households that were not interested in treating their water gave three reasons for their disinterest (Figure 3d). Cost was the biggest barrier for their interest in treating (50%). These results suggest that an affordable water treatment device is necessary. The other options for not purchasing, i.e., *water is clean thus not necessary to purchase* and *afraid to change water*, also were significant barriers to adoption of a water treatment device. Educational efforts on available water treatment technologies and their capabilities might facilitate adoption. The *interest in treating water* was incorporated in the SEM as an observed variable and provided some postulated analysis that is not in the existing literature.

3.5. Measured Water Quality. The microbial and chemical water quality parameters that were assessed are shown in Figure SI.3, grouped by the primary water sources in each of the counties. Specific parameters include heterotrophic plate count (HPC), total coliforms, *E. coli*, arsenic, and total chlorine concentration. All of the *colonias* surveyed in El Paso Country, except for Zaragosa, rely on piped water that is treated and distributed by Lower Valley Water district.

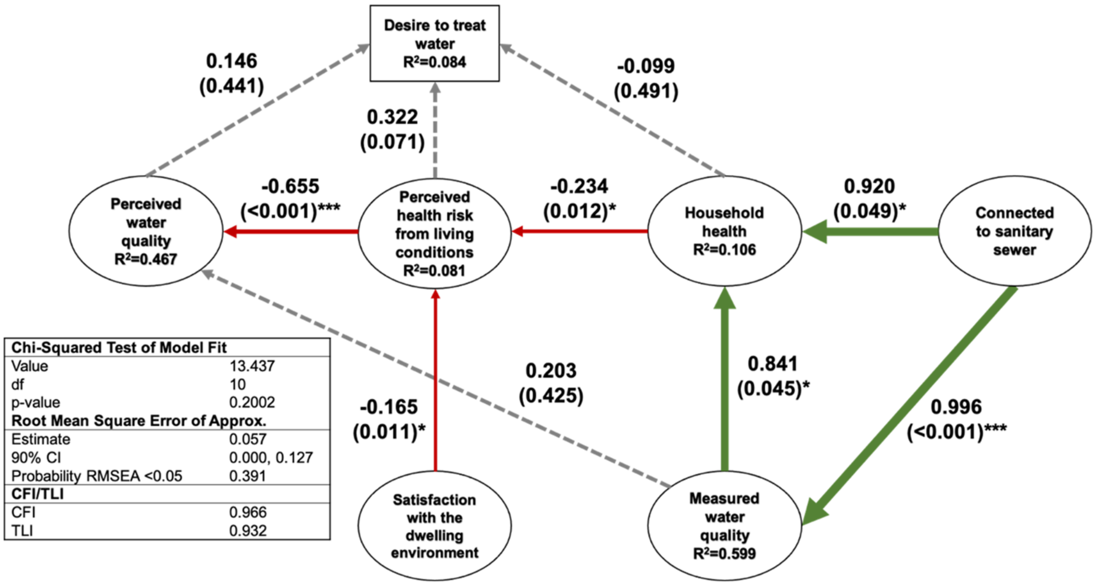

Figure 4. Structural equation model with path values. The top number on each path is the standardized path value, and the bottom parenthetic value is the *p*-value. Positive path values are shown with green arrows, and negative values are shown with red arrows. Paths with a significant *p*-value of less than 0.05 are shown with the solid line. Dashed paths are nonsignificant. Significance also is noted as $^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$. The model fit information for the structural model generated by M*plus* is displayed in the table inset. The code and output can be found in Section SI.5. One example of how to read a pathway is *satisfaction with the dwelling environment* negatively influences *perceived health risks from living conditions*, i.e., as *satisfaction with the dwelling environment* increases, *perceived health risks from living conditions* decrease. Indirect pathways also were probed, and inferences were made (Table SI.3). One-way arrows do not necessarily mean that one factor is causing another, but they represent a likely pathway of influence. Note that measured water quality parameters reflect a snapshot in time and do not capture temporal variability.

Therefore, water in these *colonias* is expected to meet USEPA regulations. All samples were well below the USEPA suggested level, 500 most probable number (MPN)/mL, for the HPC. Only one sample from the *colonia* of Fortuna tested positive for total coliforms. This sample, along with another one from Fortuna, was also below the USEPA minimum for total chlorine of 0.2 mg/L. The samples from Zaragosa were not above the allowable level of E.coli despite not having any measurable level of chlorine residual. Four samples each from different *colonias* in El Paso County (i.e., Sparks, Revolucion, Fortuna, and Los Colonias) contained arsenic ranging from 19−23 μg/L, and these values are above the USEPA's MCL of 10 μg/L.

The Starr County *colonias* that are near the Texas−Mexico border have access to treated+piped water. The more rural *colonias* in the north of the county rely on household wells. Overall, the piped water did not contain arsenic or *E. coli*, and only two household samples had HPC >500 MPN/mL. These had detectable but inadequate concentrations of chlorine (<0.2 mg/L). Both households utilize an Ionics IQ Series Whole House System for water treatment, which presumably was behind on maintenance because residents reported not completing any after installation. On the other hand, the samples from households relying on wells contained significantly elevated arsenic levels, total coliforms, and *E. coli*. Arsenic was above the MCL in all of the Starr County household wells ($n = 12$), and its concentration was as high as 65 μg/L. Total coliforms were measured in all of these wells with the exception of one, and four wells contained *E. coli*. Overall, the household wells in Starr County had higher concentrations of microbial contamination than those in the Nueces County, which could be due to the use of cesspool systems and open pits for handling sewage. These cesspool systems, which are illegal to build in most areas, lack the ability to physically and biologically treat waste, unlike septic systems. The assessment of domestic sewage as a source of groundwater contamination could be probed by microbial source tracking for human fecal markers or by caffeine analysis because caffeine is used in most households.[50−52]

The *colonias* in Nueces County rely on household or community wells without any treatment of the water prior to use. Because this water is not chlorinated, no chlorine measurements were performed. Six of the nine *colonias* there, all with household wells, had HPC >500 MPN/mL. Three of these wells tested positive for *E. coli*, suggesting fecal contamination of the water, possibly from household septic systems. It is notable that rainfall in the week prior to sampling and surveying in Nueces County caused significant flooding in the area. Further assessment of water quality in the *colonias* in this county was conducted during a dry period to evaluate seasonal variation.[4] The results revealed that well water shifted from microbial contamination after wet periods (with substantial rainfall) to arsenic contamination during dry periods (with limited rainfall for a substantial period of time), leaving the residents vulnerable to health risks throughout the year.[4]

While the findings of poor water quality (particularly in the *colonias* that rely on wells) raise concerns, most of the households do not drink water from these wells or the treated + piped supply; therefore, exposure could be limited to cooking and washing activities. It should be noted that the water quality results herein are a snapshot in time. While further longitudinal studies of water quality should be conducted, these results highlight the need for interventions to address the microbial and chemical quality of water at the POU. For the SEM, *measured water quality* was incorporated as an observed variable, where water was deemed *compliant* or *noncompliant* based on USEPA standards.

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3.6. Structural Equation Model to Explore Relationships among Factors Relating to Water. The SEM was solved simultaneously through a series of equations determined by the hypothesized model (code and output detailed in Section SI.5). Results from this analysis show pathways that link one variable directly to another (i.e., direct pathways) and pathways between variables that are mediated by one or more intervening variables (i.e., indirect pathways). These pathways provide a potential route of influence and should not be assumed to indicate direct or indirect causation. Figure 4 shows that SEM had an adequate fit by commonly used indicators.[25] Specifically, the chi-squared test for the model fit is nonsignificant, comparative fit index (CFI) and Tucker−Lewis index (TLI) are both greater than 0.9, and the confidence interval for root mean square error of approximation (RMSEA) contains 0.05. The path model (Figure 4) is shown with direct pathways between the variables. For each direct pathway, the standardized values are shown by the top value on each with its p-value noted parenthetically (and the corresponding significance indicated with an asterisk). Indirect pathways between the variables are shown in Table SI.3. The percentage of variance (i.e., R^2) explained by the model is shown for each dependent variable.

In Figure 4, the SEM pathways reveal that *connected to sanitary sewer* has a strong positive influence on *household health* (0.920, p-value = 0.049) and *measured water quality* (0.996, p-value < 0.001). The available domestic waste management systems for different *colonias* are shown in Figure 2. All *colonias* relying on sanitary sewers utilize treated + piped water. The other common management systems in the *colonias* include septic/cesspools and even open pits for wastewater (as used by one household). The pathways in the SEM from the sanitary sewer underscore that infrastructure improvements influence health and water in these communities. Although similar findings have been reported elsewhere, the infectious disease burden from unimproved sanitation in more developed nations has been reported to be relatively low.[53] The findings from the SEM highlight that even with the sanitation improvements in the U.S., some areas, e.g., *colonias*, still need support and development in this regard; however, these improvements are costly to install and require sufficient water supply (approximately 75 L/capita-d) to properly function.[54] A more appropriate alternative for some *colonias* might be nonsewered sanitation systems or decentralized wastewater treatment, which have proven to be economical and technologically feasible in underserved communities.[55,56] Policy interventions should consider sanitation improvements or better oversight of septic systems (e.g., annual inspections) as priorities due to their impact on health and water quality in the *colonias*.

As hypothesized, the model reveals that *measured water quality* (as described by the selected measures) positively influences household health (p-value = 0.045). To investigate if *colonias* residents can assess their water quality (with regard to the specific measured parameters), the direct path from *measured water quality* to *perceived water quality* was calculated. While this path is nonsignificant with no direct correlation observed, *measured water quality* does have an indirect influence on *perceived water quality* (p-value < 0.05). The purpose of probing this indirect pathway was to assess if measured water quality had an underlying impact on the residents' perception of its quality, mediated by other variables. *Household health* and *perceived health risk from current living conditions* mediate this indirect impact. Though the surveyed households did not accurately predict the measured water quality results, these water quality parameters indicate that the quality of their water could negatively impact their health and is indirectly influencing their perceived water quality; many other factors such as routine health care, diet, or other environmental or occupational exposures might also impact their health.

Post hoc exploratory analysis was completed with grouping to further probe the impact that *measured water quality* has on *perceived water quality*. First, grouping based on county was assessed, but the model fit was inadequate. However, grouping based on a household's primary water source, i.e., treated + piped water versus hauled/well water, caused the pathway between *measured water quality* and *perceived water quality* to become significant (Figures SI.6 and SI.7). Specifically, residents of *colonias* with haul/piped water are good assessors of their water quality shown by the observed positive value (0.530, p-value < 0.001). On the other hand, residents of *colonias* with treated + piped water are poor assessors of their water quality shown by the negative observed value (−0.171, p-value = 0.045). This finding demonstrates that the water source is a significant underlying factor for the accurate perception of water quality.

Analyses of the path associated with the variables designed to capture the essence of living in a *colonia*, i.e., *perceived health risk from current living conditions* and *satisfaction with the dwelling environment*, were significant. Specifically, *perceived risk from current living condition* is negatively influenced by *household health* (p-value = 0.012). In other words, the better the *household health*, the less risk that residents perceive about their current living condition and vice versa. The other variable that aims to capture the essence of living in a *colonia* is *satisfaction with the dwelling environment*, which negatively influences *perceived health risk from current living condition* (p-value = 0.011). This path can be interpreted as follows: the less satisfied the residents feel about their current living condition, the more risk of compromised health they perceive from it, demonstrating that living conditions in a *colonia* are a driving factor in residents' perception of health risks.

One of the novel aspects of this research was the assessment of factors that influence willingness to purchase a POU water treatment device, i.e., *desire to treat water*. When examining what influences the *desire to treat water*, the probed pathways were nonsignificant. This result suggests that educational interventions could be useful in showing how water treatment technologies can improve water quality and household health. This null result could be due to a large percentage of households' interest in treating their water, i.e., no matter what the loading of the dependent variables, approximately 76% of the households showed interest in treating their water.

The amount of variance explained by the model for each dependent variable is shown by the R^2 values in Figure 4. The model explains about half of the variance in *perceived water quality* (46.7%) and *measured water quality* (59.9%), suggesting that these variables are fairly well captured by the model. Conversely, the model explains only approximately 8.1% of the variance in *perceived health risk from current living condition* and about 10.6% for *household health*, indicating that some other external factors are contributing to these obtained outcomes. For example, as suggested above, health can be influenced by many other factors than considered in this model. The relatively low degree of variance explained by the model for

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these dependent variables provides evidence that the probed pathways are not fully capturing all of the independent variables and relationships. Thus, postulated pathways provide a potential route of influence but do not indicate implicit causation.

SEM was utilized to gain a quantitative understanding of the drivers for water-use practices along with the impact of water quality in the *colonias*. To date, only a handful of researchers have used SEM to explore factors relating to water.[27−34,37]This work builds on findings from previous studies and is the first to assess the impacts of *measured water quality*. The results show that *measured water quality* directly influences *household health* and indirectly influences *perceived water quality*. When grouping is assessed based on the primary water source, the impact of *measured water quality* on *perceived water quality* becomes statistically significant, demonstrating the influence that a water source can have on perception of its quality. This work also is the first to utilize SEM to explore a household's desire to treat water; however, community members did not associate health and water quality with their desire to treat water. These findings highlight the need for educational programs on commercially available water treatment technologies, their costs, and how they can improve health by targeted contaminant removal. Such educational programs have the potential to improve the quality of life for *colonias* residents while reducing their costly reliance on bottled or vending-machine water.

3.7. Implications and Potential Impact of this Work.

This research provides a comprehensive dataset on water, sanitation, health, and living conditions in *colonias* across Texas and underscores the urgent need for improvements in water quality. Household wells were found to be contaminated with arsenic (as high as 65 μg/L) and in some cases with *E. coli*. While households with treated + piped water had better water quality overall, some contained inadequate chlorine residual. The developed quantitative SEM reveals factors and relationships, where future policy interventions and educational efforts might be targeted to improve the quality of life in *colonias*. Specifically, *measured water quality* in these communities directly impacts *household health*, especially in households with wells as the primary water supply. The direct and indirect pathways established between perceived and measured water quality suggest that decision making in these communities should consider measured data (e.g., health and water quality data) and not rely solely on the perceptions of the residents. Differences in perceived and measured water quality were observed when *colonias* are grouped based on their primary water sources, where households with treated + piped water were inaccurate predictors, while those with hauled/well water were accurate predictors. *Household health* and *perceived water quality* do not correlate with the *desire to treat water*, suggesting a need for education about the available water treatment technologies and the link between water quality and health. *Connected to sanitary sewer* was found to positively influence both *household health* and *measured water quality*, indicating that infrastructure improvements should be a priority policy intervention. A strong desire to treat water before drinking was observed; however, any water treatment technology needs to be both affordable and have removal of site-specific contaminants (e.g., microorganisms and arsenic).

Colonias are unique in terms of their dynamic transition to permanence (from temporary settlements) and because of the persistent lack of appropriate water and sanitation infrastructure. Living in a relatively poor dwelling environment in a *colonia* is found to be a driving factor (i.e., significant dependent variable) in the developed model. Interestingly, residents who were more satisfied with their living conditions had lower perceived health risks. This finding has a strong likelihood for downstream decision making by the *colonia* residents; e.g., lack of focus on household or infrastructural improvements. The quantitative assessment from this study indicates the need and desire of the *colonias* residents for POU treatment, establishes that the relationship between perceived and measured water quality is dependent on water source, and identifies that the choice of drinking water in these communities is likely a cultural practice. The results are consistent across the three counties (despite their unique geographic and climatic conditions), suggesting that these are likely characteristic of *colonias* and similar unincorporated communities elsewhere. The findings from this study illustrate the immediacy of infrastructural needs in low-income communities in Texas. Similar invisible communities elsewhere in the U.S. might be experiencing sustained water stress while also having a desire to adopt and use POU treatment systems. The social and infrastructural dynamics that have been untangled through this model show a potential for the model to be adopted to determine social drivers for water-use practices in other low-income communities in the U.S. and beyond.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c05355.

Variables and justification of the relationship in the structural equation model (Table SI.1); indicator variables with their loading and *p*-values onto latent variables that were used the structural equation model (Table SI.2a); indicator variables with their loading and *p*-values onto latent variables that were not in used the structural equation model (Table SI.2b); standardized total direct and indirect effects (Table SI.3); comparison between Quick Arsenic II and ICP-MS for arsenic measurements (Figure SI.1); measured water quality (Figure SI.2); socioeconomic status grouped by county (Figure SI.3); perceived water quality grouped by county and the primary water source (Figure SI.4); desire to treat water grouped by county (Figure SI.5); structural equation model with path values for households that utilize well/hauled water as their primary source (Figure SI.6); structural equation model with path values for households that utilize treated + piped water as their primary source (Figure SI.7); survey in English (Section SI.1); survey in Spanish (Section SI.2); water sampling and testing (Section SI.3); other latent variables probed related to household health, sanitation, and living in a *colonia* (Section SI.4); and description of structural equation modeling and code utilized in *MPlus* and output from modeling (Section SI.5) (PDF)

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Notes

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