Empirical versus Perceived Water Quality in Vulnerable Puerto Rican Communities

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ABSTRACT

Water quality is a broad engineering issue that refers to water's chemical, physical, and biological characteristics and suitability for various uses, including drinking, recreation, agriculture, and industry. It is a significant challenge affecting millions worldwide and has far-reaching consequences for public health, economic development, and environmental sustainability. Poor water quality disproportionately affects disadvantaged communities and those with inequitable access to resources globally. Water quality has been a significant issue in Puerto Rico's history, particularly as the island's population and industrial development have grown. Water quality in Puerto Rico has been questionable since Hurricane Maria struck in 2017. The island's aging water infrastructure, coupled with natural hazards such as Hurricane Maria, has compounded the problem of the provision of potable drinking water on the island. Indeed, research reveals high levels of chemical and microbiological activity in the water quality before and after Hurricane Maria. These problems have caused residents on the island to form negative perceptions about their water quality despite documented efforts, such as federal bailouts to curb the existing water quality problem. The current situation may have hit residents at a crossroads because their water quality perceptions may be unfounded or justified depending on whether the tap water provided by the water utility is safe for drinking. To address this gap, this paper investigates the relationship between actual water quality derived from empirical testing and

water quality perceptions in Puerto Rico. Data collection included household surveys with residents (N = 154) from May 2022 to July 2022 and water sample collection from residents' homes (N = 137) during the same period. Mixed methods research shows that only 35% of residents consumed tap water, while 91% used bottled water. Water quality tests show that chemical water properties meet US federal standards, while microbiological water properties do not meet federal water standards. Additionally, results show significant differences between the water quality test results and the water quality perceptions across the three study communities of Loíza, Comerío, and Aguas Buenas. It also reveals that females in Puerto Rico are more likely to accurately predict water quality test results with their water quality perceptions.

INTRODUCTION

Water quality is a critical issue in the context of disadvantaged and inequitable access to water, affecting millions of people worldwide [1]. Frequently, communities bereft of access to potable water sources concurrently experience disproportionate repercussions from water pollution and contamination, intensifying pre-existing health and economic inequalities [2], [3]. Such circumstances can facilitate the proliferation of waterborne diseases and various health ramifications, especially among susceptible demographics, including children, expectant mothers, and older adults[4]. In addition, industrial activities, agricultural practices, and urbanization can all contribute to water pollution and contamination, particularly in communities that lack regulatory oversight or political power to advocate for their interests [5], [6]. These communities may also face challenges in accessing information about water quality, making it difficult to identify and address contamination issues.

Puerto Rico's water quality challenges have persisted over an extended period, with documented noncompliance with water quality standards dating back to 1995 [7], [8]. The detrimental consequences of Hurricane Maria in 2017 accentuated these challenges, revealing elevated levels of inorganic and organic trace contaminants in tap drinking water [9]. Investigations have discovered that small communities in Puerto Rico exhibit drinking water with fecal coliform concentrations surpassing the thresholds established by the Safe Drinking Water Act [10], while substandard water infrastructure has been identified as a critical

factor in the water quality contamination challenges in Puerto Rico [11]. Furthermore, increased natural hazards such as tropical storms and hurricanes have further heightened water quality contamination in Puerto Rico [10], [12], resulting in drastically diminished water quality on the island [13].

Characterized by its physicochemical and microbiological attributes pertinent to its appropriateness for domestic utilization, water quality has garnered heightened scrutiny on the island [14], [15]. Prior to Hurricane Maria in Puerto Rico, previous research indicates that management approaches varied depending on the water-distributing institution, such as the Puerto Rico Aqueduct and Sewer Authority (PRASA), versus community-managed non-government entities[8]. Households in government-administered communities exhibited a higher propensity to boil and filter tap water, stemming from perceptions of suboptimal water quality[8]. In contrast, residents of non-government water-supplied communities tended to obtain water from multiple sources, including wells[8]. Overall, 64.2% of the island's inhabitants express a generalized distrust of tap drinking water supplied by PRASA [16]. In addition, literature shows that people's primary drinking water sources or water consumption behaviors result from their perception of drinking water quality in places with mistrust.

A key component of this mistrust is the individuals' perception of water quality, which often dictates their consumption behavior and choice of water sources [17]. Perceptions of water quality can be influenced by factors such as taste, odor, color, and the presence of contaminants, as well as social, cultural, and historical contexts [18], [19]. Consequently, these perceptions can shape individuals' decisions to opt for alternative water sources, like bottled water or private wells, even when the primary water supply meets established safety standards [17], [20].

Nevertheless, while these water quality perceptions may align with reports in the literature about substandard water quality [16], there may be times when these water quality perceptions misalign with the actual chemical and microbiological water results [19], [21]. Moreover, little is known about whether people accurately understand water quality and how their social perceptions of tap water quality correspond to the actual water quality test results. The research gap in the literature is addressed by asking, *"Does the actual water quality align with water quality perceptions in Puerto Rico?"* Additionally," *What are the*

Commented [IZ1]: here is of both PRASA customers and non costumer right?

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sociodemographic differences in alignments or misalignments of actual water quality with water quality perceptions in Puerto Rico?" The study hypothesizes that the water consumption behaviors in Puerto Rico have shifted from tap drinking water to other sources in the aftermath of Hurricane Maria due to negative water quality perceptions. In addition, it also hypothesizes a misalignment of empirical water quality and the perceived water quality in Puerto Rico. The outcomes of this study may offer valuable understanding regarding water consumption patterns influenced by the congruence or discordance between individuals' perceptions of water quality and the actual water quality. Such knowledge can prove instrumental in helping government and non-government entities make decisions to improve water quality and the infrastructure used to deliver it.

WATER QUALITY PERCEPTION IN PUERTO RICO

Water quality, a constituent of global water insecurity, is highly susceptible to the impacts of hurricanes. The devastating effects of Hurricane Maria in Puerto Rico caused flash floods that wreaked havoc on water infrastructure and distribution systems, leading to a prolonged post-hurricane recovery period [9], [12], [22], [23]. Preceding Hurricane Maria, studies highlighted persistent issues regarding access to safe drinking water in Puerto Rico, with concerns such as high levels of bacteria, contaminants, and aging infrastructure being reported. The hurricane's aftermath further exacerbated the situation with significant damage to the water infrastructure and widespread contamination of floodwaters, power outages, and other contributing factors [16]. Studies conducted after Hurricane Maria found that the storm significantly impacted water quality and access, with many communities experiencing prolonged periods without access to safe drinking water. These communities faced significant chemical and microbiological contamination levels in tap drinking water provided by the Puerto Rico Aqueduct and Sewer Authority (PRASA) [24]. Almost all communities with drinking water sources from PRASA in severe violations of the United States Environmental Protection Agency (US EPA) water standards did not return to compliance [25]. The adverse water quality was a significant concern for residents, with many reporting illnesses and other health problems related to contaminated water [16].

The prevailing challenges with water quality in Puerto Rico may have impacted the perceptions of the island's residents. Water quality perception is defined as how the residents on the island view or feel about their water quality and its suitability for consumption [18], [19], [21]. Water quality perceptions can be formed at any time due to sensory information (organoleptic), risk perception, collective or shared experiences, external information about the water quality, or trust in the water utility companies or regulators on the island [18], [26]. Notably, water quality perceptions have a direct impact on the water consumption behavior of a community. People are more inclined to drink water from sources they perceive positively. It is commonly assumed that water quality is directly related to safety and palatability, thus emphasizing the importance of water quality perception in determining water consumption behavior. Prior experience, particularly the taste of the water, has a decisive role in forming water quality perception [18], [19].

Although previous studies have evaluated the alignment of water quality perceptions to their corresponding actual water quality, there is still a gap in studying the alignment of perceptions and actual water quality after natural disasters such as Hurricane Maria. It is essential to address this gap because natural hazards may amplify negative water quality perceptions, hampering disaster recovery efforts. Such an investigation ensures safe drinking water delivery to Puerto Rico's residents.

METHODOLOGY

The study employs a mixed methods approach in Loíza, Comerío, and Aguas Buenas communities in Puerto Rico. Data was collected through the administration of surveys (N=154) and water sample collection (N=137) from respondents' households in the communities above from May to June 2022. The present study focuses on three geographical areas: Loíza, Comerío, and Aguas Buenas. Loíza is a densely populated municipality with a predominantly Black-Hispanic demographic, situated 39 kilometers (24 miles) east of San Juan's capital city. Comerío is predominantly inhabited by White-Hispanic individuals and is 44 kilometers (27 miles) south of San Juan. Aguas Buenas, also predominantly White-Hispanic, is positioned centrally in the territory of Puerto Rico. These three municipalities were selected based on the significant

damage to their water infrastructure during Hurricane Maria. In the aftermath of Hurricane Maria, the residents of these communities lacked access to safe drinking water for close to two months. Even today, these communities face challenges concerning the supply of safe drinking water due to aging piping infrastructure and frequent power outages.

A combination of quota and purposive sampling was used to survey a population of people aged 18 and over who had experienced flooding due to Hurricane Maria. The surveys were administered in person by one of four trained Spanish-speaking research assistants under the supervision of a PhD student from Iowa State University. All research participants received a $25 Walmart gift card as compensation for their time. The surveys collected information on the demographics of the research participants, including age, gender, income, educational levels, years of residency, and race. In addition to demographics, the surveys were used to collect data on all the various types of drinking water sources (tap, filtered tap, well, stream, harvested rain, and bottled water) that residents used. To capture the water quality perceptions, the water quality perceptions scale, derived from perception items in the literature [18], [19], was used to collect residents' perceptions of chlorine, hardness, alkalinity, lead, copper, chloride, and Escherichia coli. All participants' households had their water tested for chemical properties and microbiological activity, following US EPA standards. Water sampled in Puerto Rico was analyzed for alkalinity, nitrite, nitrate, hardness, chloride, total organic carbon (TOC), color, and Escherichia coli following EPA methods 100-A, 114-A, 106-A, 105-A, 415.3, 140-A, and 1103.1, respectively. Alkalinity, nitrite, nitrate, hardness, chloride, and color were measured using a SEAL AQ2 Discrete Analyzer (SEAL Analytical, Mequon, WI). TOC was measured using a Shimadzu Wet Chemical Oxidation Total Organic Carbon Analyzer- TOC-VWS (Shimadzu Corporation, Kyoto, Japan). The Iowa State University Institutional Review Board reviewed the study to ensure ethical research with human subjects, and all research assistants were trained on IRB requirements before administering surveys. Table 1 shows the water quality perceptions and corresponding water test parameters.

163 Table 1 Water Quality Perceptions and Corresponding Water Quality Tests.

Water Quality Perception	Water Quality Test
There are health risks associated with drinking water in my home from my tap	Escherichia coli
I am happy with the taste of my tap water	Chlorine (Free and Total)
	Alkalinity
I am happy with the color of my tap water	Color
I am happy with the smell of my tap water	Chlorine (Free and Total)
Tap water has caused health problems for me or for someone in my family.	Escherichia coli
My tap water is contaminated with lead or any chemicals.	Copper
	Nitrate/Nitrite
My tap water has too much chlorine.	Chlorine (Free and Total)
My tap water has too much limescale	Hardness (CaCO3)
My tap water is too hard	Hardness (CaCO3)
I am worried about the quality of water and water contamination (e.g., chemicals) after hurricane season 18	Escherichia coli
	Copper

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165 **RESULTS**

166 **Primary Drinking Water Sources**

167 The results from our surveys indicate that 35% of respondents rely on tap water as a drinking water source,
168 while another 31% use filtered tap water. In contrast, 91% of survey respondents use bottled water as a
169 drinking source. Wells, harvested rainwater, and streams are also used at lower rates than bottled water
170 (36%, 12%, and 17%, respectively). Table 2 shows the demographic distribution of residents and their water
171 consumption behaviors.

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Table 2 Demographic Distribution of Residents and Their Water Consumption Behaviors.

Demographic	N	Descriptive Statistics	Value
Age	154	Mean Age	63.01
		Median Age	66
Gender	154	Male	25.3%
		Female	74.0%
		Non- Binary	0.7%
Residency (Years)	154	Mean (Years)	55.06
		Median (Years)	61
Education	152	Up to Elementary	10.53%
		Middle School	9.21%
		High School	47.37%
		Bachelor's/Associate	31.58%
		Other	1.32%
Race	126	Black	36.5%
		White	36.5%
		Mixed	22.2%
		American Indian/Alaska Native	2.4%
		Other	2.4%
Primary Drinking Water Sources	154	Tap Water	35%
		Filtered Tap Water	31%
		Bottle Water	91%
		Wells	36%
		Harvested Rainwater	12%
		Streams / Rivers	17%

Water Quality Tests

The test results obtained from Iowa State University's Environmental Engineering laboratories show that the chemical properties of water in Puerto Rico generally meet the federal water standards of the US EPA. However, there is evidence of the presence of microbiological activity (*E. coli*) in the water provided by PRASA. Table 3 shows the average water properties in Puerto Rico concerning the federal water standards set by the US EPA.

Table 3 Water Quality Test Results

Water Quality Test	Loíza	Comerío	Aguas Buenas	US EPA Standard
Chemical				
Alkalinity	81.9 mg/L	67.0 mg/L	64.4 mg/L	20 to 200mg/L
Copper	6.99E-7 mg/L	0.00073 mg/L	3.7E-6 mg/L	1.0 mg/L
Lead	0 mg/L	0 mg/L	0 mg/L	0 mg/L
Nitrite	0.88 mg/L	0.201 mg/L	0.714 mg/L	1 mg/L
Nitrate	0.88 mg/L	0.201 mg/L	0.714 mg/L	10 mg/L
Hardness (CaCO3)	144.4157 mg/L	132.4955 mg/L	194.96 mg/L	300 mg/L
Chloride	55.11 mg/L	56.71 mg/L	28.03 mg/L	250 mg/L
Color	-0.56909 units	-0.99326 units	-1.74771units	15 color units
Chlorine (Free)	0.95mg/L	0.50mg/L	0.43mg/L	4.0mg/L
Chlorine (Total)	1.06mg/L	0.56mg/L	0.51mg/L	4.0mg/L
Microbiological				
E.coli	Present	Present	Present	No presence

T Test Results

One of the study's goals aimed to examine the alignment or misalignment of water quality perceptions and water quality test results. Independent sample t-tests were used to analyze the mean differences between the two groups shown in Table 1. The tests revealed statistically significant mean differences for water quality perceptions of chlorine versus the water quality test results for free and total chlorine. The 20 residents who reported had positive perceptions of their chlorine levels ($M = 0.89$, $SD = 0.47$) compared to the 121 participants who expressed negative perceptions of their chlorine levels ($M = 0.583$, $SD = 0.46$) demonstrated significantly higher free chlorine test results, $t(141) = 2.74$, ($p = 0.0109$). Similarly, the 20 residents who reported positive perceptions of their chlorine levels ($M = 1.01$, $SD = 0.52$) compared to the 120 participants who expressed negative perceptions of their chlorine levels ($M = 0.68$, $SD = 0.47$) demonstrated significantly higher total chlorine test results, $t(140) = 2.62$, ($p = 0.0145$). The study's results indicate a statistically significant difference between the mean test scores of the water quality perceptions of chlorine and the actual water quality of chlorine test results.

Interaction Effects Between Water Quality Taste Perceptions and Gender On Chlorine Test Results

Table 4 presents the results of the regression models, including the interaction effects of taste perceptions and gender on free chlorine water test results. These were tested by creating an interaction term by

multiplying taste perception (positive versus negative) and gender (women versus men). As shown in the table, results indicated a significant effect of the interaction term. Post hoc probing to decompose this significant interaction [27] is depicted in Figure 1 and indicated that among women, taste perceptions negatively and moderately predicted free chlorine test results (simple slope = -0.404, $p<0.0000$), but among men, taste perceptions positively and steeply predicted free chlorine test results (simple slope = 0.447, $p<0.001$) such that women plus positive taste perception predicts higher free chlorine test results. In other words, women with negative chlorine water quality taste perceptions generally had lower total chlorine test results.

Table 4. Interaction effect regression analysis of water quality taste perceptions and gender predicting free chlorine test results.

Free Chlorine Tests	Coef.	SE	t-value	p-value	[95% Conf. Interval]		Sig
Age	0.006	0.003	2.09	0.039	0.000	0.012	**
Gender	-0.164	0.139	-1.17	0.244	-0.441	0.113	
Race	-0.155	0.029	-5.29	0.000	-0.212	-0.097	***
Education	0.010	0.039	0.27	0.790	-0.067	0.088	
Taste Perception	-0.081	0.092	-0.88	0.380	-0.262	0.100	
Taste Perception x Gender	0.441	0.186	2.38	0.019	0.073	0.809	**
Constant	0.800	0.285	2.81	0.006	0.235	1.366	***

R-squared	0.2784	Number of obs	116
F-test	7.01	Prob > F	0.000

*** *p<.01*, ** *p<.~~05, *~~05, * p<.1*

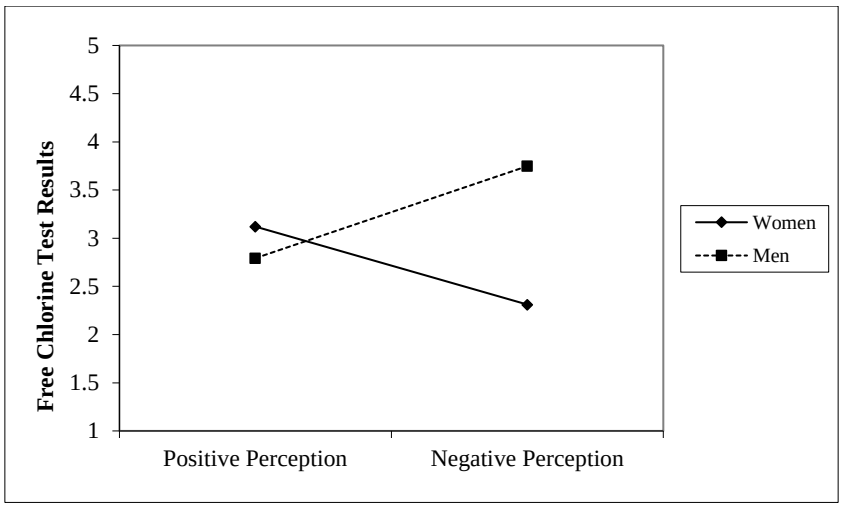

Figure 1. Free chlorine test results as a function of water quality taste perception and gender

Similarly, Table 5 presents the results of the regression models, including the interaction effects of taste perceptions and gender on total chlorine water test results. Figure 2 indicated that among women, taste perceptions negatively and moderately predicted free chlorine test results (simple slope = -0.318, $p<0.0000$), but among men, taste perceptions positively and steeply predicted free chlorine test results (simple slope = 0.564, $p<0.000$) such that women plus positive taste perception predicts higher total chlorine test results. It shows that women who expressed negative chlorine water quality taste perceptions generally had lower total chlorine test results.

225 Table 5. Interaction effect regression analysis of water quality taste perceptions and gender predicting free

226 chlorine test results.

Total Chlorine Tests	Coef.	SE	t-value	p-value	[95% Conf. Interval]		Sig
Age	0.004	0.003	1.39	0.169	-0.002	0.010	
Gender	-0.094	0.149	-0.63	0.530	-0.388	0.201	
Race	-0.155	0.031	-5.00	0.000	-0.216	-0.094	***
Education	0.004	0.414	0.09	0.930	-0.078	0.085	
Taste Perception	0.005	0.097	0.05	0.957	-0.188	0.199	
Taste Perception x Gender	0.349	0.197	1.77	0.080	-0.042	0.739	*
Constant	0.973	0.302	3.22	0.002	0.373	1.572	***

R-squared	0.2707	Number of obs	112
F-test	6.50	Prob > F	0.000

**** p<.01, ** p<.05, * p<.1*

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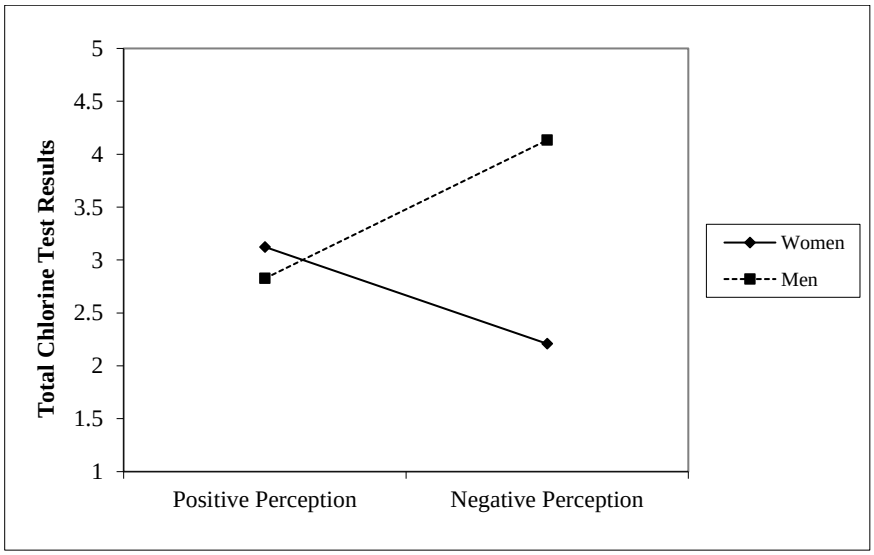

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229 Figure 2. Total chlorine test results as a function of water quality taste perception and gender

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DISCUSSION

This study's results demonstrated a significant misalignment between the objective chemical water quality and residents' perceptions of the chemical water quality in Puerto Rico. While residents expressed concerns about the hardness, chlorine, color, and alkalinity of their drinking water, laboratory tests revealed that all these parameters were within acceptable standards as per federal standards [28]. There are several reasons why residents in Puerto Rico may hold negative perceptions about their drinking water quality, despite the chemical water quality properties meeting federal standards. Puerto Rico's drinking water history with contamination [25], [29] may have left a lasting impression on the residents, leaving a lingering mistrust of the water supplied by PRASA. The aftermath of Hurricane Maria may also be a contributing factor that has led to widespread water quality issues, which still affect residents' perceptions today. The aging and deteriorating water infrastructure impacted by the hurricane may have also contributed to the negative perceptions of the water quality provided through this water infrastructure. Many communities in Puerto Rico still rely on outdated water infrastructure, which may affect the appearance and taste of the water [8], [30], [31]. As a result, most of these residents now rely heavily on alternative drinking water sources such as bottled water or augmenting their tap drinking water using a filter. The mistrust of tap drinking water has spiraled since Hurricane Maria [16].

While the chemical properties of the drinking water provided by the Puerto Rico Aqueduct and Sewer Authority (PRASA) seem to meet all US Environmental Protection Agency (EPA) federal standards, there is still substantial microbiological contamination in the water. This may be due to damages and breaks in the distribution systems, which allow for post-treatment contamination before the water reaches end users [32]. Microbiological contamination may cause serious health outcomes such as diarrheal diseases [9], [13], [25]. The residents of Puerto Rico may have already experienced such health issues, which could contribute to their negative perceptions of water quality. This aligns with research suggesting that personal experience with waterborne illnesses can significantly impact public perception of drinking water safety [18], [19]. A potential cause of microbiological contamination in the water distribution system is the aging and

deteriorating water infrastructure in Puerto Rico. Many communities still rely on outdated infrastructure susceptible to leaks and breaks [33]. These issues lead to water loss and create opportunities for contaminants to enter the water supply, particularly during periods of low pressure [32].

Finally, this study's results demonstrated that women in Puerto Rico were more likely to have accurate perceptions of their water quality than men, who tended to overestimate the quality of their drinking water. This phenomenon could be explained by the traditional and stereotypical gender roles in the Caribbean, where men are generally seen as breadwinners. At the same time, women are responsible for managing the household, including monitoring water quality [34], [35]. The findings from Puerto Rico align with a broader global pattern, where gendered roles in water, sanitation, and hygiene (WASH) often place women at the forefront of managing household water resources [36], [37]. In many cultures, women are responsible for water collection, storage, and treatment, which can influence their perceptions of water quality and their understanding of the risks associated with contaminated water [37].

This study recommends further research into this misalignment and how to improve it to ensure that residents are not spending on alternative water sources when they have good drinking water provided by PRASA.

CONCLUSION

Puerto Rico's water quality recovery after Hurricane Maria has been a long and painful process for residents living on the island. Residents in Loiza, Comerio, and Aguas Buenas have to bear the brunt of the poor water quality provided by PRASA despite the widely publicized and documented efforts made by federal and local governments to fix the water quality issue. Following a mixed research method, we found that only 35% of residents rely on the tap drinking water provided by PRASA. Additionally, 91% of residents rely on bottled water as a drinking source. We also identified that the tap water meets the required chemical water standards set by the US EPA, with severe microbiological contamination evident in the presence of

E coli. This research highlights differences between the water quality perceptions and water quality tests in Puerto Rico.

To address the issues found in this study and improve public perception of water quality in Puerto Rico, it is essential to invest in the maintenance and upgrade of water infrastructure, increase transparency and communication about water quality testing and results, and engage communities in water management decisions. Public awareness campaigns and educational programs can also help to build trust in the water supply system and ensure that residents have accurate information about the quality of their drinking water.

In conclusion, access to safe drinking water is a fundamental human right. The water crisis in Puerto Rico is a complex issue that requires immediate attention and action. Addressing the residents' concerns regarding the quality of tap drinking water provided by PRASA should be a top priority. The government and relevant stakeholders must work together to ensure safe drinking water delivery to all Puerto Rico residents.

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