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Puerto Rico's Water Supply: An Investigation of the Levels of Trihalomethanes and Other Contaminants

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Abstract

The US Commonwealth of Puerto Rico is comprised of 143 islands, atolls, cays, and islets. Of the 143 localities, only 3 islands are inhabited: The mainland (often referenced as Puerto Rico), Culebra, and Vieques. To properly analyze the water supply quality, the mainland will be the focal point for examining environmental and social injustices. Puerto Rico is a racially diverse but ethnically homogenous territory, with most of the commonwealth living below the poverty level. Access to clean water sources is always tenuous in Puerto Rico. Over 70 percent of the island is served by water, violating US health standards. However, the recent hurricanes made the situation even more detrimental. According to data reported between January 2015 and March 2018 by the Consumer Confidence Report (CCR), 97 percent of the population of Puerto Rico utilizes a common drinking water system with one or more recent violations of the Safe Drinking Water Act for its testing requirements for lead and copper levels. The amounts found were far higher than any US state, meaning that virtually everyone on the island gets water from systems that violated testing or reporting requirements. In this study, we have collected and analyzed the levels of trihalomethanes (THMs), haloacetic acids (HAAs), copper, lead, and total organic compounds (TOCs) in drinking water providing systems in Puerto Rico and compared them with the recommended levels of contaminants provided by the US Environmental Protection Agency (EPA) guidelines. Many of these reported contaminants can have serious and detrimental health effects after prolonged exposure to higher concentrations of the contaminants found in the drinking water sources of Puerto Rico.

Keywords

Water Quality, Social Disparity, Puerto Rico, Contaminants, Household

Income, Income Per Capita, Environmental Justice, Hurricane Maria

1. Introduction

The international standards for drinking water were established in 1958 by the World Health Organization (WHO) and revised in 1963 and 1971, creating the Guidelines for Drinking Water Quality (GDWQ) (World Health Organization, 2022). These water quality guidelines are under continuous revision based on the newest scientific evidence available, provided by rigorous testing studies. In 1974 the US created the Safe Drinking Water Act (SDWA) to protect the standards for the quality of drinking water. As part of the SDWA, the Environmental Protection Agency (EPA) establishes the minimum standards to protect tap water. These rules require all owners or operators of public water works systems to comply with these primary (health-related) standards and the treatments required to maintain optimal water quality (United States Environmental Protection Agency, 2022a). In 1996, the SDWA was amended to require using the best and most current peer-reviewed scientific research to make any change for establishing current standards (United States Environmental Protection Agency, 2022b). Regular water quality testing is required based on the standards issued by the EPA to ensure water quality compliance with the law. The required testing results performed throughout the year must be reported to consumers by sending and posting a Consumer Confidence Report (CCR) annually (Eastern Water Quality Association, 2023). The guidelines and standards for drinking water quality are vital since water is essential for life. The Centers for Disease Control and Prevention (CDC) recommends drinking eight 8-ounce glasses of water daily, or 3.7 L of water for men and 2.7 L for women (Eastern Water Quality Association, 2023). These standards are required to control drinking water contaminated with pathogens, harmful organic or inorganic matter, and other pollutants. Routine testing allows the water to be treated to help prevent disease outbreaks and other dire health effects.

2. Water Contaminants and Regulations

Drinking water quality varies depending on the condition of the water source and the treatment it receives, but it must meet US Environmental Protection Agency (EPA) standards and regulations. The underlying importance of water is understood, albeit violations do occur even with EPA standards in place. Once a violation occurs, it must be reported to the EPA, while the EPA is responsible for the CCR for informing the consumer of the water quality (United States Environmental Protection Agency, 2022b). The levels of contaminants found in drinking water have been studied by scientists at various agencies, such as the non-profit corporation Environmental Work Group (EWG). The EWG specializes in determining the links between tested chemical compounds found in a water source and the environmental consequences, even if the levels of the compound are within legal limits assigned by the EPA (Environmental Working Group, 2023). Previous studies in our lab found a correlation between the levels of trihalomethanes (THMs), annual household income, and poverty levels (Guha et al., 2019). Other studies showed water quality disparities regarding the level of heavy metals exposure in the drinking water of Tennessee (Beni et al., 2019). Previous research on the correlation between water quality and poverty levels shows that there should be a high correlation to the water quality in Puerto Rico, especially after Hurricane Maria caused catastrophic circumstances, leading even more citizens to live below poverty limits.

Our primary exposure to environmental hazards is unsafe drinking water. The EPA is responsible for writing regulations to enforce water quality legislation, such as the National Primary Drinking Water Regulations, the National Primary Drinking Water Regulations Implementation, and the National Secondary Drinking Water Regulations (Baum et al., 2015). However, the EPA only requires the regulations of public drinking water systems that service at least 15 connections or more than 25 persons. The Safe Drinking Water Act of 1974 requires public drinking water systems to monitor the presence of certain contaminants at specific intervals of time and at mandatory locations to ensure compliance allowing violations to be reported to the Safe Drinking Water Information System Federal Reporting Services (SDWIS/FED), created in 1995 (Raucher, 2003). Although, a 2002 EPA audit found that only 62% of violations are ever reported, and states are only required to report a violation, not the contamination levels. These protocol violations leave citizens with only the knowledge of a possible violation, not the specifics of the violation (United States Environmental Protection Agency, 2016a).

2.1. Contaminants in Drinking Water from Puerto Rico

Hurricane Maria, a category 4 storm, landed south of Yabucoa Harbor in Puerto Rico in September 2017, resulting in catastrophic flash floods and island-wide devastation (Brown et al., 2018). It destroyed over 90% of the electrical grid and more than 80% of the agricultural sectors, leaving large areas without water services. The devastation has resulted in an abysmal economic situation leaving many of its citizens below the poverty level (Subramanian et al., 2018). Limited studies on the impact of Hurricane Maria have reported increasing rates of adverse physical and psychological health consequences and hurricane-exacerbated environmental effects, including deterioration of the drinking water quality in Puerto Rico (Hernandez et al., 2020). However, very little is known about the disruption of drinking water quality in Puerto Rico after Hurricane Maria, which is critical to water-related contamination and the correlation between disease control and public health concerns (Cook et al., 2008).

Environmental pollution in Puerto Rico was extensive even before Maria, with over 200 hazardous waste sites, including 18 active Superfund sites contaminated by pesticides, chlorinated volatile organic compounds (CVOCs), other organic compounds, and heavy metals such as copper and lead (United States Environmental Protection Agency, 2020). Recent studies have reported that Hurricane Maria-impaired regional coastal waters in Puerto Rico due to disrupted water runoff (Miller et al., 2019). This runoff triggered the release of various toxic substances into source waters, ultimately degrading drinking water quality and lacking effective water treatment systems (Reardon, 2017). In 2020, increased phthalate levels in urine in Puerto Rico provided evidence of hurricane-affected chemical exposures primarily via contaminated drinking water sources (Watkins et al., 2020). Another water quality study focusing on microbial contamination after two back-to-back hurricanes (Irma and Maria) on St. Thomas pointed out the urgent need for cistern water management to prevent the ingestion of waterborne diseases caused by contaminated drinking water (Jiang et al., 2020). Post-disaster toxicological studies of drinking water quality for Hurricane Maria in Puerto Rico have not yet been reported, making the identities of the priority water pollutants likely to pose health risks due to Hurricane Maria unclear and even more critical to our research.

Drinking water contains many regulated and unregulated contaminants at trace levels from various environmental pollution sources and water treatment processes, with known or unknown toxic effects on exposed human populations (Fang et al., 2019; Richardson & Ternes, 2017). Previous disaster research on water quality often focused on a single group of chemicals (Watkins et al., 2020), which does not reflect the complexity of chemical mixtures in drinking water supplies exacerbated by hurricane events (Murray et al., 2010). This study provides a comprehensive evaluation of Hurricane Maria's impact on drinking water quality and associated toxicity effects in Puerto Rico by integrating analysis of both inorganic and organic trace pollutants with high throughput based on economical household poverty rates. Furthermore, the correlational analysis probes the potential relationships between detected chemical levels in water quality reports, annual household income, and possible environmental or health outcomes that will contribute to our understanding of post-hurricane evolution and dynamics of complex contaminant mixtures such as levels of THMs, HAAs, copper, lead, and TOCs in drinking water. Our report will provide timely yet informative results for initial toxicity screening on drinking water quality and risk identification that can be potentially incorporated into a post-disaster water resource management strategy.

Exposure to THMs, HAAs, copper, lead, and TOCs can have serious adverse health effects after prolonged exposure to higher contaminants. **Table 1** shows common contaminants found in the drinking water supply found in Puerto Rico, along with their relative limits, sources, and potential health risks associated with their exposure. The limits and sources for each contaminant are listed in every CCR next to the level of the report.

2.2. Effects of Contamination Exposure

The contamination of drinking water can lead to many potential adverse health

Table 1. Common drinking water contaminants with their relative limits, sources, and potential health effects (United States Environmental Protection Agency, 2016a).

Contaminants	Limits	Sources	Potential Health Effect
Lead	0.15 mg/L	Erosion of natural resources, household plumbing corrosion	Birth Defects, Infant Mortality, Down Syndrome, Kidney Disease
Copper	1.3 mg/L	Corrosion of household plumbing, erosion of natural deposits, leaching of wood preservatives	Nausea, Headache, Nose Bleeds, Liver Damage, Fatal Hemolysis Vomiting, Diarrhea, Stomach Cramps
Residual Chlorine	4 mg/L	Disinfectant added to control pathogens	Nervous System Damage, Anemia, Methemoglobinemia
Trihalomethane: chloroform bromodichloromethane dibromochloromethane bromoform	80 mg/L	By-product of water chlorination	Cancer, Liver Disease, Kidney Failure, Nervous System Damage, Bladder Cancer, Colorectal Cancer, Adverse development, and reproductive effects during pregnancy
Haloacetic Acids: trichloroacetic acid dichloroacetic acid monochloroacetic acid dibromoacetic acid monobromoacetic acid	60 mg/L	By-product of water chlorination	Cancer, Liver Disease, Kidney Failure, Spleen Damage, Bladder Cancer, Colorectal Cancer, Adverse development, and reproductive effects during pregnancy
Total Organic Carbon	2%	Naturally present in the environment	Cancer, Chemical Carcinogens, Chills, Fever, Shock, Adverse development, and reproductive effects during pregnancy

effects, harming the economy of an impoverished community such as Puerto Rico. Table 1 lists the most common side effects caused by minimal exposure to contaminated drinking water. Infants, children, preteens, pregnant women, and those with compromised immune systems are at the highest potential risk. Contaminated drinking water is linked to diseases such as Cholera, Dysentery, Hepatitis, Polio, gastrointestinal illnesses, reproductive issues, and neurological disorders (World Health Organization, 2019). The WHO estimates that approximately 830,000 people die from diarrhea caused by exposure to unsafe drinking water annually (World Health Organization, 2019). Infants and pregnant mothers living in areas with contaminated drinking water have a higher incidence of lower birth weights, which decreased by approximately 14.6%, and spontaneous and premature labor increased by 10.3% (Vodela et al., 1997). Other recent studies provided evidence of strong correlations associated with THMs, HAAs, and TOCs exposures with low birth weights, neural tube defects, and spontaneous abortions (Bove et al., 2002). Any contaminant exposure can impede the development of bones, which can have long-lasting effects on bone density and rickets (Vodela et al., 1997). The mild effects of healing from exposure can harm household budgets due to a lack of access to affordable healthcare. Those who do not succumb to the sickness will lose available income during recovery. In 2004, it was estimated that 143,000 lives were lost to lead poisoning, and the loss of million years of life adjusted to disease and recovery were lost worldwide (Brown & Margolis, 2012).

3. Materials and Methods

Based on the 2010 United States Geological Survey (USGS) water-use statistics (Molina-Rivera, 2014), approximately 99% of Puerto Rico's freshwater domestic use (population served:96%) was from Puerto Rico Aqueducts and Sewers Authority (PRASA) water supplies, with the remaining 1% of domestic use comprising small, non-PRASA community water supply (NPCWS; domestic use: 0.75%; population: 3%) or self-supply (SS; domestic use: 0.25%; population served: 1%; primarily private wells) (Molina, 2015; Molina-Rivera, 2014). EPA is not authorized to regulate or monitor self-supply, defined as fewer than 15 connections and 25 people (United States Environmental Protection Agency, 2021b). For the one-time, pilot-scale spatial assessment, a single TW sample was collected in August 2018 from 14 locations (7 commercial locations, all PRASA; 7 residential locations including 3 PRASA, 3NPCWS, and 1 private well) spatially distributed across Puerto Rico.

3.1. Materials

All water quality data was collected and prepared for descriptive statistical analysis from secondary data related to drinking water quality obtained from the annual water safety report for the counties in Puerto Rico. Data, including median annual household income for a family of four, was collected from the United States Census Bureau (United States Census Bureau, 2020). Additional data was collected by directly contacting Puerto Rico water service offices to obtain information not readily available in the annual PRASA and non-PRASA water safety reports (Autoridad de Acueductos y Alcantarillados de Puerto Rico, 2023a), "Informe sobre la calidad del agua" and Autoridad de Acueductos y Alcantarillados de Puerto Rico (2023b), "Regiones operacionales".

3.2. Methods

The contaminant levels for each water system were collected by viewing the CCR for each water system provided on the website for Autoridad de Acueductos y Alcantarillados (AAA) de Puerto Rico, in English is known as Puerto Rico as shown in **Figure 1**.

Tables list and organize income per capita for the counties (provided by the Census Bureau) along with their drinking water compliance sources (provided by PRASA and non-PRASA water services departments) and correlated to the levels of contaminants. The average household income for a family of 4 in different metropolitan areas (n-12) and their water quality are shown using multi-variable charts. **Table 2** features the specific cities being analyzed in this study. Additional information regarding safe water violations was gathered from SDWIS/FED for Puerto Rico's (n-6) highest and (n-6) lowest-income cities. The

Figure 1. Puerto Rico travel regions—OpenStreetMap (Fitzgerald, 2013).

Table 2. Puerto Rico's water system regions (World Health Organization, 2022).

Metro	Norte (North)	Sur (South)	Este (East)	Oeste (West)
Bayamón	Arecibo	Adjuntas	Aguas Buenas	Aguada
Canóvanas	Barceloneta	Arroyo	Aibonito	Aguadilla
Carolina	Camuy	Coamo	Barranquitas	Añasco
Cataño	Ciales	Guánica	Caguas	Cabo Rojo
Guaynabo	Corozal	Guayama	Cayey	Hormigueros
Loíza	Dorado	Guayanilla	Ceiba	Isabela
San Juan	Florida	Juana Díaz	Cidra	Lajas
Toa Baja	Hatillo	Maunabo	Comerío	Las Marías
Trujillo Alto	Jayuya	Orocovis	Culebra	Maricao
	Lares	Patillas	Fajardo	Mayagüez
	Manatí	Peñuelas	Gurabo	Moca
	Morovis	Ponce	Humacao	Rincón
	Naranjito	Salinas	Juncos	Sábana Grande
	Quebradillas	Santa Isabel	Las Piedras	San Germán
	Toa Alta	Villalba	Luquillo	San Sebastian
	Utuado	Yauco	Naguabo	
	Vega Alta		Río Grande	
	Vega Baja		San Lorenzo	
			Vieques	

violations include all data collected since the formation of the SDWIS/FED until 2020. SDWIS/FED is reported and updated regularly during inspections.

Additional information for each water system was obtained from the EPA website using the Safe Drinking Water Information System (SDWIS) (United States Environmental Protection Agency, 2022b). The SDWIS provided the primary water source, the number of violations, and the population served for each water system. If a municipality has more than one water system, an average of the contaminant levels for each system was taken. An Excel file from the United States Geological Survey (USGS) (United States Geological Survey, 2014) provides the water systems that serve each of the municipalities.

The median household income, population data, and % of persons in poverty were retrieved from the United States Census Bureau for the 2010 (United States

Census Bureau, 2021) and 2020 (United States Census Bureau, 2022) censuses. The data was obtained by accessing the QuickFacts website for the Census Bureau. Since the release of the 2020 census, QuickFacts has shown the information from the current census. The population information is reported for 2010 and 2020.

3.3. Maximum Cumulative Ratio (MCR) Calculation

To untangle contaminant interactions of complex mixtures, the recently introduced maximum cumulative ratio (MCR) concept to identify potentially high-risk mixtures that may require further investigation and the major chemicals possibly driving the cumulative risk in tap water samples (De Brouwere et al., 2014). When calculating hazard quotient (HQ), permitted doses were selected as regulatory United States Environmental Protection Agency (USEPA) Maximum Contaminant Levels (MCLs) for regulated contaminants under the Safe Drinking Water Act (SDWA). Mapping analyses of chemicals and contaminant toxicity levels were conducted in ArcGIS Desktop 10.2 (http://resources.arcgis.com/en/help/main/10.2/index.html).

Concentrations of organic contaminants were natural log transformed to approximate a normal distribution more closely. The Kolmogorov-Smirnov test (National Institutes of Standards and Technology, 2023) was used for data distribution patterns. All chemical and toxicity data were standardized by creating *z*-scores to minimize the effects of varying chemical concentrations (Akman et al., 2019). An unpaired *t*-test was used to evaluate contaminant concentration differences between pre-hurricane and post-hurricane samples. Only the contaminants with $p < 0.05$ in both tests were considered significant.

3.4. Statistical Analysis

Statistical data analysis was performed using ANOVA and Student's t-test. Data were initially compared within a given experimental setup by ANOVA (Qualtrics, 2023). A significant ANOVA was followed by a pairwise analysis of control versus exposed data using Student's *t*-test; a *p*-value of less than 0.05 was considered significant.

4. Results and Discussion

The oldest and most populous US territory, Puerto Rico has an annual income for a family of four of $11,315 (Puerto Rico Poverty Level – PRPL), which is approximately 43 percent of the federal poverty level (FPL) of the US: $26,500 for a family of four annually in 2020 (United States Census Bureau, 2020). According to the 2020 United States Census, the population of Puerto Rico has a median age of 42.4 years, with a 3.26 million annual income loss, or a decrease of 1.89 percent after Hurricane Maria in 2018. After compiling the secondary data, population size, annual income, and water quality for 12 major metropolitan cities in Puerto Rico (**Table 3** and **Figure 2**). The mean (M) metropolitan population

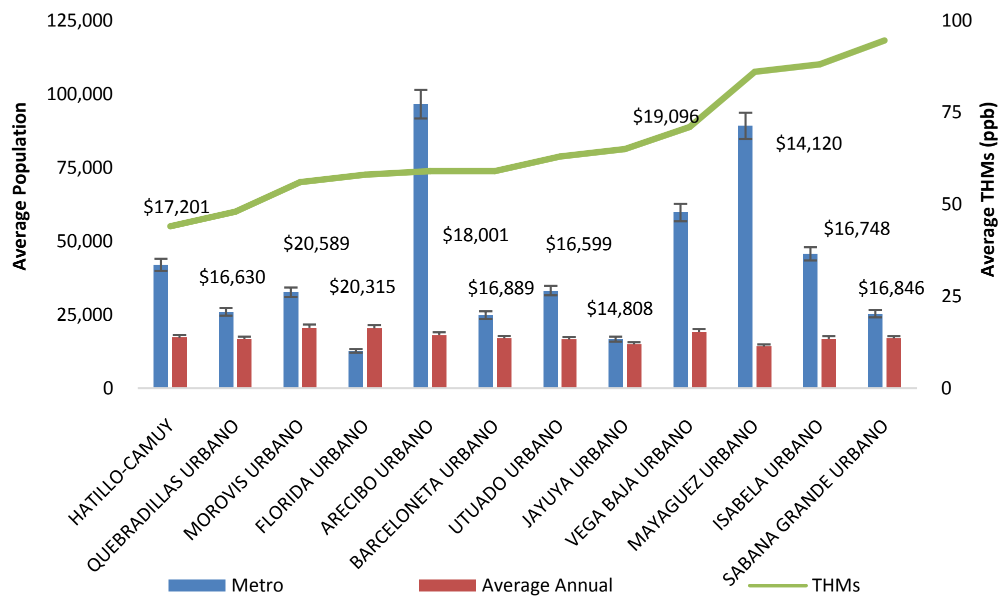

Figure 2. Average analysis data, regulated TTHMs per population size and annual income major metropolitan area in Puerto Rico (2016-2020).

Table 3. Average (2016-2020) census data, city, population size, average household income, and the level of THMs (ppb).

Water Service System Provider	Average Population	Average Household Income	TTHM (ppb)
Hatillo-Camuy	41,953	$17,201	44
Quebradillas Urbano	25,919	$16,630	48
Morovis Urbano	32,610	$20,589	56
Florida Urbano	12,680	$20,315	58
Arecibo Urbano	96,440	$18,001	59
Barceloneta Urbano	24,816	$16,889	59
Utuado Urbano	33,149	$16,599	63
Jayuya Urbano	16,642	$14,808	65
Vega Baja Urbano	59,662	$19,096	71
Mayaguez Urbano	89,080	$14,120	86
Isabela Urbano	45,631	$16,748	88
Sabana Grande Urbano	25,265	$16,846	95

is 41,987 with a standard deviation (SD) of 26,982, a household income of M = $17,320, SD = $1944, and water quality (THMs) M = 66 ppb, SD = 4.6 ppb. When comparing the average (n-6) of the lowest-income communities with (n-6) higher-income communities (M = $18,681 and 57.8 ppb) and lower-income communities (M = $15,958 and 71.6 ppb), which was statistically significant $t = 2.48$ and $p = 0.027$ (1 tailed ANOVA).

There is a significant correlation between annual income and water quality, implying that lower-income communities are 1.9 times more likely to drink contaminated water than higher-income communities. Contributing to the need for ongoing public-health research into the potential role of drinking water contaminant exposures in Puerto Rico with adverse health outcomes, informing source-water sustainability and drinking-water treatment decision-making, and supporting interstudy comparison and a cohesive national perspective on cumulative contaminant risk at the drinking-water point of contaminant exposures.

Tables 4-8 represent the PRASA Consumer Confidence Reports for Water for constituents; Chlorine Residual-distribution system [ppm], Copper [ppm], Lead [ppm], Trihalomethanes (THM) [ppb], Haloacetic Acids (HAA) [ppb] and Control of Disinfection By-Product Precursors (TOC) [ppm] for five consecutive years of 2016-2020. Secondary data related to drinking water quality was obtained from the annual water safety report for the major areas of Puerto Rico. (Water and Sewer Authority (PRASA) United States Environmental Protection Agency, 2023).

After compiling the secondary data for the 2016 water quality of 12 major water systems in Puerto Rico (**Table 4** and **Figure 3**), complete reports filed (n-48) M = 78.3 ppb with an SD ± 19.8 for TTHMs, M = 59.3 ppb with an SD ± 14.8 for HAAs, M = 1.33 ppm with an SD ± 0.25 for chlorine, M = 1.33 ppm with SD ± 0.30 for Copper and M = 5.82 ppm with an SD ± 0.40 for levels of lead reported for 2016.

Table 4. Consumer confidence report for Puerto Rico 2016 (PRASA: United States Environmental Protection Agency, 2023).

2016 Puerto Rico Water System Provider	Chlorine [ppm]	Copper [ppm]	Lead [ppm]	TTHM [ppb]	HAA [ppb]	TOC [TT]
Hatillo-Camuy	1.64	0.18	5.2	51.7	33.0	1.50
Quebradillas Urbano	1.19	0.20	6.0	66.0	34.0	1.22
Morovis Urbano	1.15	0.20	6.0	72.0	66.0	1.99
Florida Urbano	1.33	0.27	6.0	56.0	51.0	0.00
Arecibo Urbano	1.52	0.22	5.0	54.0	48.0	1.50
Barceloneta Urbano	1.40	0.23	5.0	57.0	49.0	***
Utuado Urbano	1.93	0.21	6.0	75.0	65.0	0.88
Jayuya Urbano	1.09	0.30	6.0	81.0	89.0	1.00
Vega Baja Urbano	1.23	0.20	6.0	110.0	51.0	1.20
Mayaguez Urbano	1.51	0.25	6.0	101.0	70.0	2.02
Isabela Urbano	1.05	0.97	6.0	86.0	60.0	1.32
Sabana Grande Urbano	1.24	0.20	6.0	103.0	69.0	1.20

Note. Major Domestic PRASA, Puerto Rico Aqueducts, Sewers Authority drinking water samples. Red indicates EPA critical exceedances violations (for TOC TT ≥ 1.0). ***No reported data.

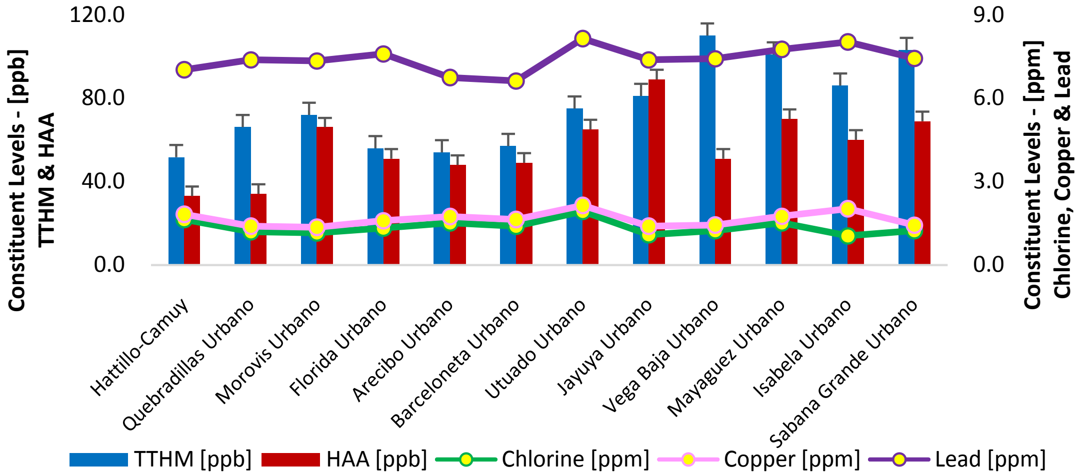

Figure 3. PRASA consumer confidence reports for 2016 for water for constituents; Chlorine Residual-distribution system [ppm], Copper [ppm], Lead [ppm], Trihalomethanes (THM) [ppb], and Haloacetic Acids (HAA) [ppb].

Table 5. Consumer confidence report for Puerto Rico 2017 (PRASA: United States Environmental Protection Agency, 2023).

2017 Puerto Rico Water System Provider	Chlorine [ppm]	Copper [ppm]	Lead [ppm]	TTHM [ppb]	HAA [ppb]	TOC [TT]
Hatillo-Camuy	1.91	0.2	6.0	51.0	33.0	1.52
Quebradillas Urbano	1.36	0.2	6.0	56.0	35.0	2.14
Morovis Urbano	1.46	0.2	6.0	64.0	61.0	2.02
Florida Urbano	1.29	0.27	6.0	63.0	52.0	0.00
Arecibo Urbano	1.5	0.34	11.6	54.0	50.0	1.33
Barceloneta Urbano	1.28	0.23	5.0	56.0	46.0	***
Utuado Urbano	1.93	0.21	6.0	79.0	76.0	0.86
Jayuya Urbano	1.56	0.08	1.6	67.0	84.0	1.00
Vega Baja Urbano	1.34	0.2	6.0	92.0	49.0	1.68
Mayaguez Urbano	1.48	0.25	6.0	81.0	50.0	1.18
Isabela Urbano	1.36	0.97	6.0	83.0	54.0	1.02
Sabana Grande Urbano	1.95	0.2	6.0	101.0	69.0	1.73

Note. Major Domestic PRASA, Puerto Rico Aqueducts, Sewers Authority drinking water samples. Red indicates EPA critical exceedances violations (for TOC TT ≥ 1.0). *** No reported data.

After compiling the secondary data for the 2017 water quality of 12 major water systems in Puerto Rico (**Table 5** and **Figure 4**), complete reports filed (n-48) M = 70.6 ppb with an SD ± 15.8 for TTHMs, M = 54.9 ppb with an SD ± 14.3 for HAAs, M = 1.54 ppm with an SD ± 0.23 for chlorine, M = 0.28 ppm with SD ± 0.24 for Copper and M = 6.02 ppm with an SD ± 0.63 for levels of lead reported for 2017.

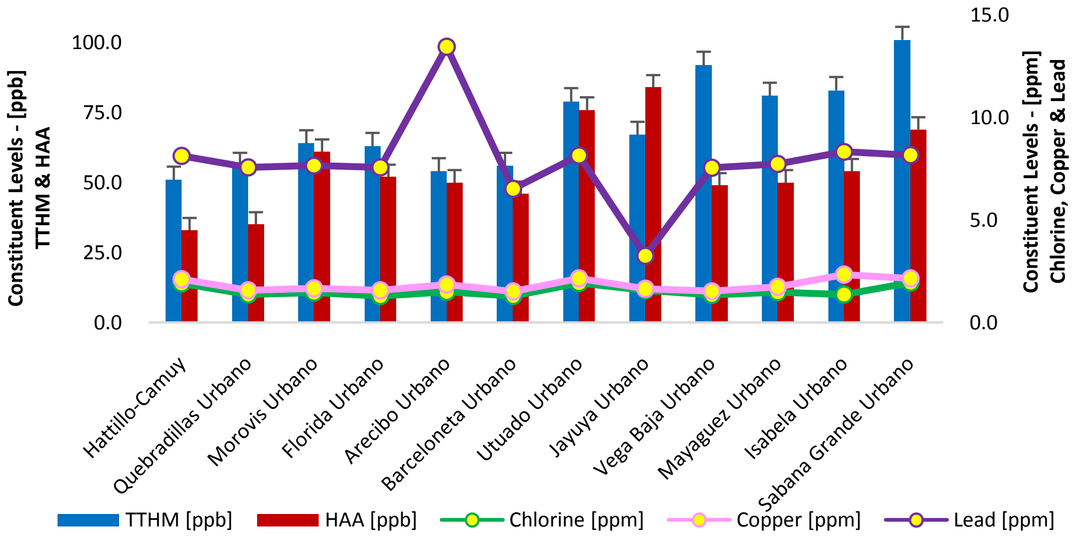

Figure 4. PRASA consumer confidence reports for 2017 for water for constituents; Chlorine Residual-distribution system [ppm], Copper [ppm], Lead [ppm], Trihalomethanes (THM) [ppb], and Haloacetic Acids (HAA) [ppb].

After compiling the secondary data for the 2018 water quality of 12 major water systems in Puerto Rico (Table 6 and Figure 5), complete reports filed (n-48) M = 66.8 ppb with an SD ± 17.9 for TTHMs, M = 49.3 ppb with an SD ± 18.2 for HAAs, M = 1.56 ppm with an SD ± 0.23 for chlorine, M = 0.45 ppm with SD ± 0.55 for Copper and M = 3.37 ppm with an SD ± 0.95 for levels of lead reported for 2018.

After compiling the secondary data for the 2019 water quality of 12 major water systems in Puerto Rico (Table 7 and Figure 6), complete reports filed (n-48) M = 65.3 ppb with an SD ± 16.2 for TTHMs, M = 44.5 ppb with an SD ± 14.5 for HAAs, M = 1.42 ppm with an SD ± 0.17 for chlorine, M = 0.52 ppm with SD ± 0.61 for Copper and M = 3.20 ppm with an SD ± 0.35 for levels of lead reported for 2019.

After compiling the secondary data for the 2020 water quality of 12 major water systems in Puerto Rico (Table 8 and Figure 7), complete reports filed (n-48) M = 59.1 ppb with an SD ± 15.2 for TTHMs, M = 44.0 ppb with an SD ± 14.9 for HAAs, M = 1.45 ppm with an SD ± 0.25 for chlorine, M = 0.13 ppm with SD ± 0.14 for Copper and M = 3.33 ppm with an SD ± 0.81 for levels of lead reported for 2020.

After compiling the secondary data collected for the 2015-2020 water quality of 12 major water systems in Puerto Rico (Figure 8), complete reports filed (n-72) M = 66.2 ppb with an SD ± 15.9, p value = 4.00E−03 for THMs, M = 49.8 ppb with an SD ± 13.8, p value = 5.06E-04 for HAAs, M = 1.44 ppm with an SD ± 0.24, p value = 0.037 for chlorine, M = 0.32 ppm with SD ± 0.04 for Copper and M = 5.00 ppm with an SD ± 1.32 for levels of lead (p values based on one-tailed ANOVA).

In August 2020, a synoptic pilot assessment of 2 organic (copper and lead)

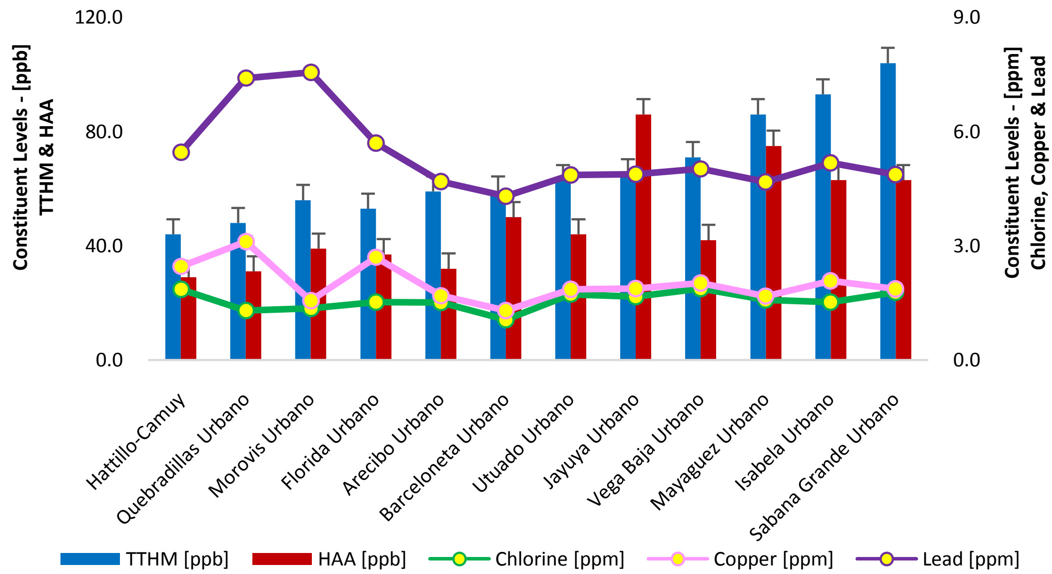

Figure 5. PRASA consumer confidence reports for 2018 for water for constituents; Chlorine Residual-distribution system [ppm], Copper [ppm], Lead [ppm], Trihalomethanes (THM) [ppb], and Haloacetic Acids (HAA) [ppb].

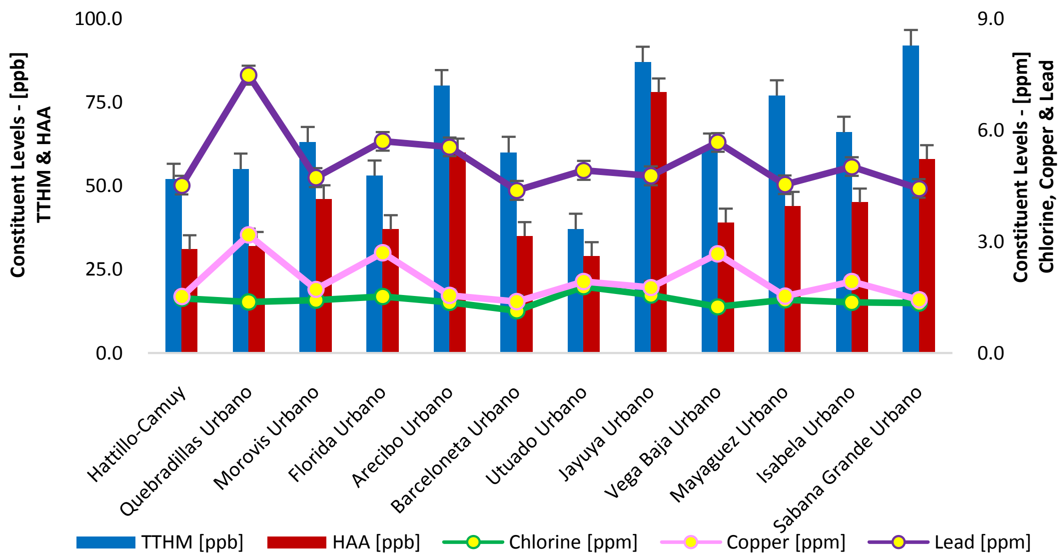

Figure 6. PRASA consumer confidence reports for 2019 for water for constituents; Chlorine Residual-distribution system [ppm], Copper [ppm], Lead [ppm], Trihalomethanes (THM) [ppb], and Haloacetic Acids (HAA) [ppb].

Table 6. Consumer confidence report for Puerto Rico 2018 (PRASA: United States Environmental Protection Agency, 2023).

2018 Puerto Rico Water System Provider	Chlorine [ppm]	Copper [ppm]	Lead [ppm]	TTHM [ppb]	HAA [ppb]	TOC [TT]
Hatillo-Camuy	1.86	0.60	3.0	44.0	29.0	1.14
Quebradillas Urbano	1.30	1.81	4.3	48.0	31.0	1.13
Morovis Urbano	1.36	0.20	6.0	56.0	39.0	2.09

Continued

Florida Urbano	1.52	1.18	3.0	53.0	37.0	***
Arecibo Urbano	1.51	0.18	3.0	59.0	32.0	1.38
Barceloneta Urbano	1.06	0.24	3.0	59.0	50.0	0.00
Utuado Urbano	1.73	0.13	3.0	63.0	44.0	1.00
Jayuya Urbano	1.67	0.21	3.0	65.0	86.0	0.96
Vega Baja Urbano	1.88	0.14	3.0	71.0	42.0	1.09
Mayaguez Urbano	1.58	0.10	3.0	86.0	75.0	1.00
Isabela Urbano	1.52	0.56	3.1	93.0	63.0	1.09
Sabana Grande Urbano	1.78	0.09	3.0	104.0	63.0	1.17

Note. Major Domestic PRASA, Puerto Rico Aqueducts, Sewers Authority drinking water samples. Red indicates EPA critical exceedances violations (for TOC TT ≥ 1.0). ***No reported data.

Table 7. Consumer confidence report for Puerto Rico 2019 (PRASA: United States Environmental Protection Agency, 2023).

2019 Puerto Rico Water System Provider	Chlorine [ppm]	Copper [ppm]	Lead [ppm]	TTHM [ppb]	HAA [ppb]	TOC [TT]
Hatillo-Camuy	1.47	0.05	3.0	52.0	31.0	1.00
Quebradillas Urbano	1.37	1.81	4.3	55.0	32.0	0.97
Morovis Urbano	1.42	0.30	3.0	63.0	46.0	1.97
Florida Urbano	1.52	1.18	3.0	53.0	37.0	***
Arecibo Urbano	1.36	0.19	4.0	80.0	60.0	1.32
Barceloneta Urbano	1.14	0.24	3.0	60.0	35.0	***
Utuado Urbano	1.79	0.13	3.0	37.0	29.0	1.00
Jayuya Urbano	1.56	0.21	3.0	87.0	78.0	0.84
Vega Baja Urbano	1.25	1.42	3.0	61.0	39.0	***
Mayaguez Urbano	1.43	0.10	3.0	77.0	44.0	1.13
Isabela Urbano	1.36	0.56	3.1	66.0	45.0	1.15
Sabana Grande Urbano	1.34	0.09	3.0	92.0	58.0	1.04

Note. Major Domestic PRASA, Puerto Rico Aqueducts, Sewers Authority drinking water samples. Red indicates EPA critical exceedances violations (for TOC TT ≥ 1.0). ***No reported data.

Table 8. Consumer confidence report for Puerto Rico 2020 (PRASA: United States Environmental Protection Agency, 2023).

2020 Puerto Rico Water System Provider	Chlorine [ppm]	Copper [ppm]	Lead [ppm]	TTHM [ppb]	HAA [ppb]	TOC [TT]
Hatillo-Camuy	1.70	0.00	3.0	45.0	35.0	0.00
Quebradillas Urbano	1.55	0.10	4.3	57.0	33.0	0.02
Morovis Urbano	1.34	0.20	3.0	49.0	35.0	0.46
Florida Urbano	1.42	0.10	3.0	38.0	56.0	***
Arecibo Urbano	1.41	0.10	5.5	58.0	39.0	0.74

Continued

Barceloneta Urbano	1.29	0.20	3.0	71.0	39.0	0.29
Utuado Urbano	1.75	0.10	3.0	38.0	27.0	***
Jayuya Urbano	1.87	0.20	3.0	83.0	80.0	1.15
Vega Baja Urbano	1.13	0.10	3.0	57.0	44.0	0.29
Mayaguez Urbano	1.43	0.00	3.0	68.0	37.0	0.97
Isabela Urbano	1.00	0.50	3.1	63.0	45.0	0.18
Sabana Grande Urbano	1.45	0.00	3.0	82.0	58.0	0.19

Note. Major Domestic PRASA, Puerto Rico Aqueducts, Sewers Authority drinking water samples. Red indicates EPA critical exceedances violations (for TOC TT ≥ 1.0). ***No reported data.

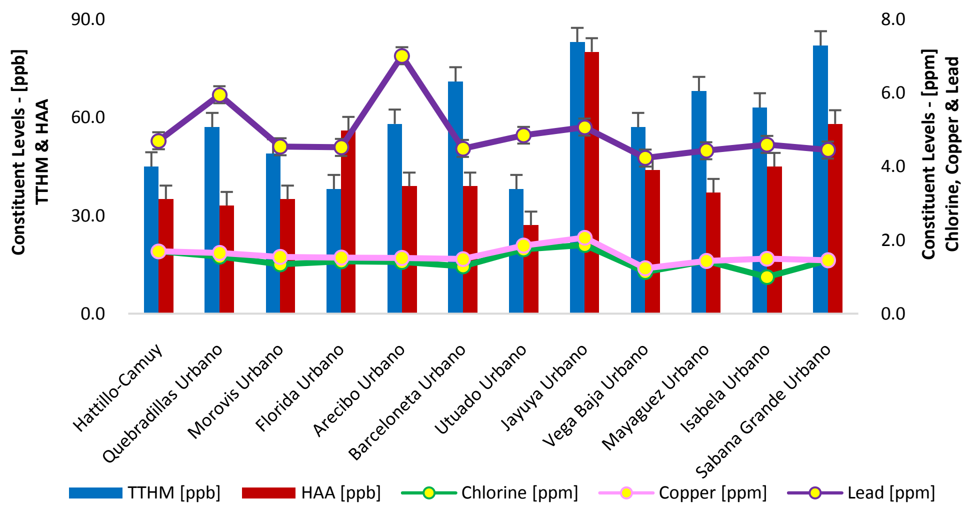

Figure 7. PRASA consumer confidence reports for 2020 for water for constituents; Chlorine Residual-distribution system [ppm], Copper [ppm], Lead [ppm], Trihalomethanes (THM) [ppb], and Haloacetic Acids (HAA) [ppb].

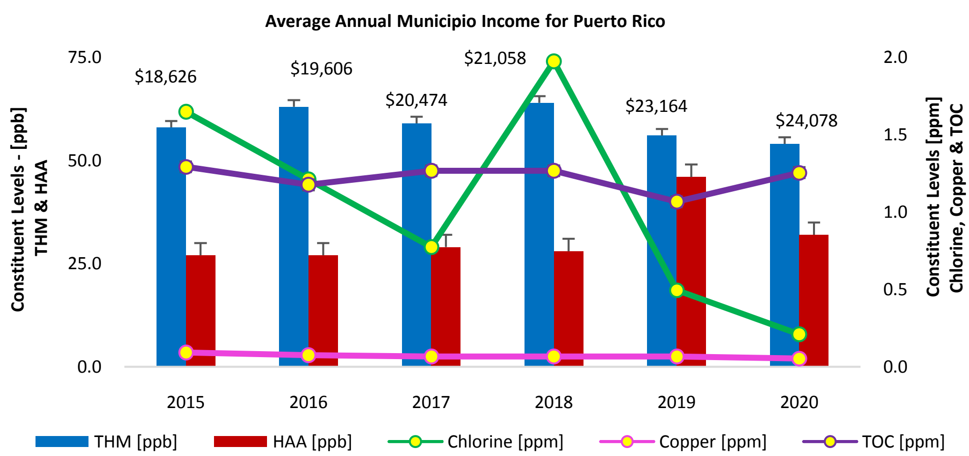

Figure 8. Average analysis data, consumer confidence report for major metropolitan water systems in Puerto Rico (2015-2020) for constituents; Copper [ppm], Chlorine Residual-distribution system [ppm], Trihalomethanes (THM) [ppb], Haloacetic Acids (HAA) [ppb] and Control of Disinfection By-Product Precursors (TOC) [ppm].

and 4 inorganic (HAA, THM, VOC, and TOC) chemicals was conducted in 14 locations across Puerto Rico. The three most reported drinking water violations were all located in Puerto Rico. **Table 9** shows secondary data of average analysis detections of regulated and unregulated inorganic and organic analytes that are common in the August 2020 synoptic drinking water sampling in 14 major Puerto Rico metropolitan cities as seen **Figure 9**. Data shows the various analytes found in drinking water for 97% of the population of all of Puerto Rico, (M) for Cu is 411.9 μg·L^{-1}, Pb is 4.3 μg·L^{-1}, HAAs is 55.6 μg·L^{-1}, THMs is 51.2 μg·L^{-1}, VOCs is 0.9 μg·L^{-1}, and TOCs is 66.9 μg·L^{-1}, respectively. A secondary pilot-scale expanded target assessment of mixtures of inorganic and organic contaminants in drinking water was conducted in Puerto Rico to inform exposures and corresponding estimations of cumulative human-health risks across the US.

Metropolitano water system, serving San Juan. San Juan has the highest number of total water quality violations at 256, followed by the Ponce Urbano system with 180 violations and the Aguadilla system with 126 violations on average. The Metropolitano water system had the highest number of total health-based violations

Table 9. Concentrations (μg·L^{-1}) of copper (Cu) and lead (Pb), and trihalomethanes (THM) cumulative detections (#) and concentrations (μg·L^{-1}) of contaminant classes detected in synoptic drinking water samples collected from 14 major metropolitan areas.

Location		ID	Source	Inorganic		Organic Class (sum detections and classifications)							
				Cu	Pb	HAAs		THMs		VOCs		TOCs	
				μg/L	μg/L	#	μg/L	#	μg/L	#	μg/L	#	μg/L
Metro	**San Juan**	C1	PRASA	292.0	**	3	**111.64**	1	**106.08**	7	0.3	2	**114.56**
Metro	Carolina	C2	PRASA	**714.0**	4.4	2	73.69	2	70.81	9	0.3	3	**152.78**
West	Aguadilla	C3	PRASA	**2290.0**	2.0	1	**107.32**	2	**94.49**	2	**2.0**	2	**114.53**
West	Mayaguez	C4	PRASA	17.7	**	0	65.93	1	63.59	0	**	0	65.76
East	Cayey	C5	PRASA	400.0	2.7	0	10.93	4	10.25	6	0.2	2	11.70
East	Humacao	C6	PRASA	324.0	**	0	52.11	1	41.27	0	**1.2**	0	53.31
North	Manati	C7	PRASA	**830.0**	**10.5**	0	40.96	6	38.56	4	**3.2**	2	45.52
South	Espino	D1	PRASA	154.0	**	0	**78.34**	1	77.39	0	0.2	1	94.48
North	Dorado	D2	PRASA	21.6	**	1	62.82	0	51.23	0	**	0	66.24
North	Toa Alta	D3	PRASA	134.0	1.9	0	**92.54**	1	**91.38**	5	0.1	2	**102.92**
North	Jayuya	D4	NPCWS	3.9	**	0	32.04	0	31.44	0	**	0	49.87
North	Utuado	D5	NPCWS	314.0	**	0	44.65	1	34.90	0	0.1	0	48.62
North	Lares	D6	NPCWS	144.0	**	0	2.87	0	2.87	0	**	1	6.17
North	Manati	D7	SS	128.0	**	0	2.84	2	2.57	2	0.5	3	9.72

Note. C = Commercial Samples D = Domestic Samples PRASA, NPCWS, and SS indicate Puerto Rico Aqueducts, Sewers Authority, and non-PRASA community-water-supply and private well-supply drinking water samples.) **Red** indicates EPA critical exceedances violations # indicates the number of violations reported that quarter ** No reported data (United States Environmental Protection Agency, 2021a).

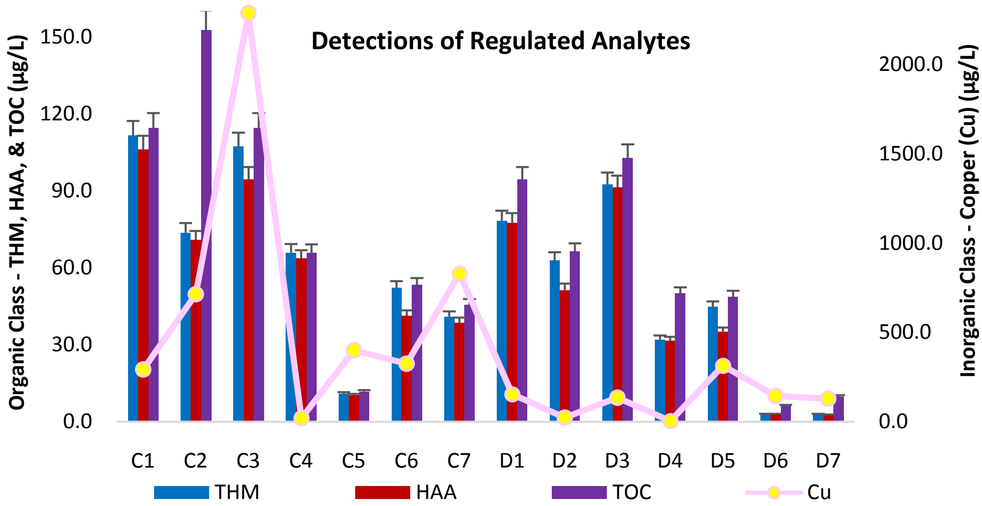

Figure 9. Average analysis data, detections of regulated and unregulated inorganic and organic analytes were common in the August 2020 synoptic drinking water sampling in major Puerto Rico metropolitan areas (United States Environmental Protection Agency, 2021a).

at 85, followed by the Aguadilla system at 62, with the Metropolitano system with 36 acute heath-based violations, the highest in the nation by a large margin for 2016-2020. Approximately 99 percent of PR's population (96% PRASA; 3% NPCWS) relies on public-supply drinking water (Molina, 2015), which is regulated, monitored, and treated for NPDWR drinking-water contaminants under the SDWA (United States Environmental Protection Agency, 2021a). On average, there are approximately 607 violations of the Lead and Copper Rule annually by the reported 158 systems that serve 3.4 million people. Most of the violations were for failure to test for lead or to report problems to health authorities and the public. 97.2 percent of the population of Puerto Rico has been served by metropolitan water systems in violation of the US Lead and Copper Rule. In many cases, water samples exceeded EPA's Lead Action Level, which is not an enforceable standard but indicates excessive lead in water (United States Environmental Protection Agency, 2021a). Based on current SDWIS data, PR has the highest rate of violation of SDWA rules in the US.

5. Conclusion

Intense hot spots of SDWA violations and increasing time trends are detected in the US, especially in Puerto Rico. Notably, repeat violations are prevalent in locations of intense spatial clustering of violations. Water systems in these locations are prone to recurring issues; repeat violations have been a focus of EPA regulation in recent years. Violation occurrence is found to be associated with low-income, rural areas. These findings indicate the need for greater regulatory oversight and assistance in achieving consistent compliance with drinking water quality standards. The compliance gap between low-income rural areas and more urban counties was significant in Puerto Rico. We also find that low-income, minority communities may face a higher likelihood of specific violations, such as the Lead and Copper Rule and total THMs. Currently, the SDWA only regulates contaminants that frequently occur at harmful levels nationwide. An important area for future research is assessing the welfare implications of uniform, national-level standards compared with subnational standards. Last, there is a nationwide need for improved data collection and monitoring of violations. Underreporting of SDWA violations deserves attention, given that estimated 26% - 38% of health-based violations are either not reported or inaccurately reported to the national SDWIS database. A complete record of violations is crucial for addressing potential public health concerns. Overall, this study indicates a need for a more directed approach to increasing drinking water quality regulations compliance for Puerto Rico. Reducing water quality violations can lead to improved health outcomes and less disparity in water service.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Abbreviations

EPA	Environmental Protection Agency
SDWIS/FED	Safe Drinking Water Information System/Federal Reporting Services
PRASA	Puerto Rico Aqueducts and Sewers Authority
CCR	Consumer Compliance Report
CDC	Centers for Disease Control and Prevention
MWR	Major Water Report
CCL	Contaminant Candidate List
WHO	World Health Organization
USEPA	US Environmental Protection Agency
USGS	United States Geological Survey
THM	Trihalomethanes
HAA	Haloacetic Acids
TOC	Total Organic Carbons
VOC	Volatile Organic Compounds
MCR	Maximum Cumulative Ratio
MCL	Maximum Contaminant Levels